Large GEM Detectors for Tracking at Forward Rapidities

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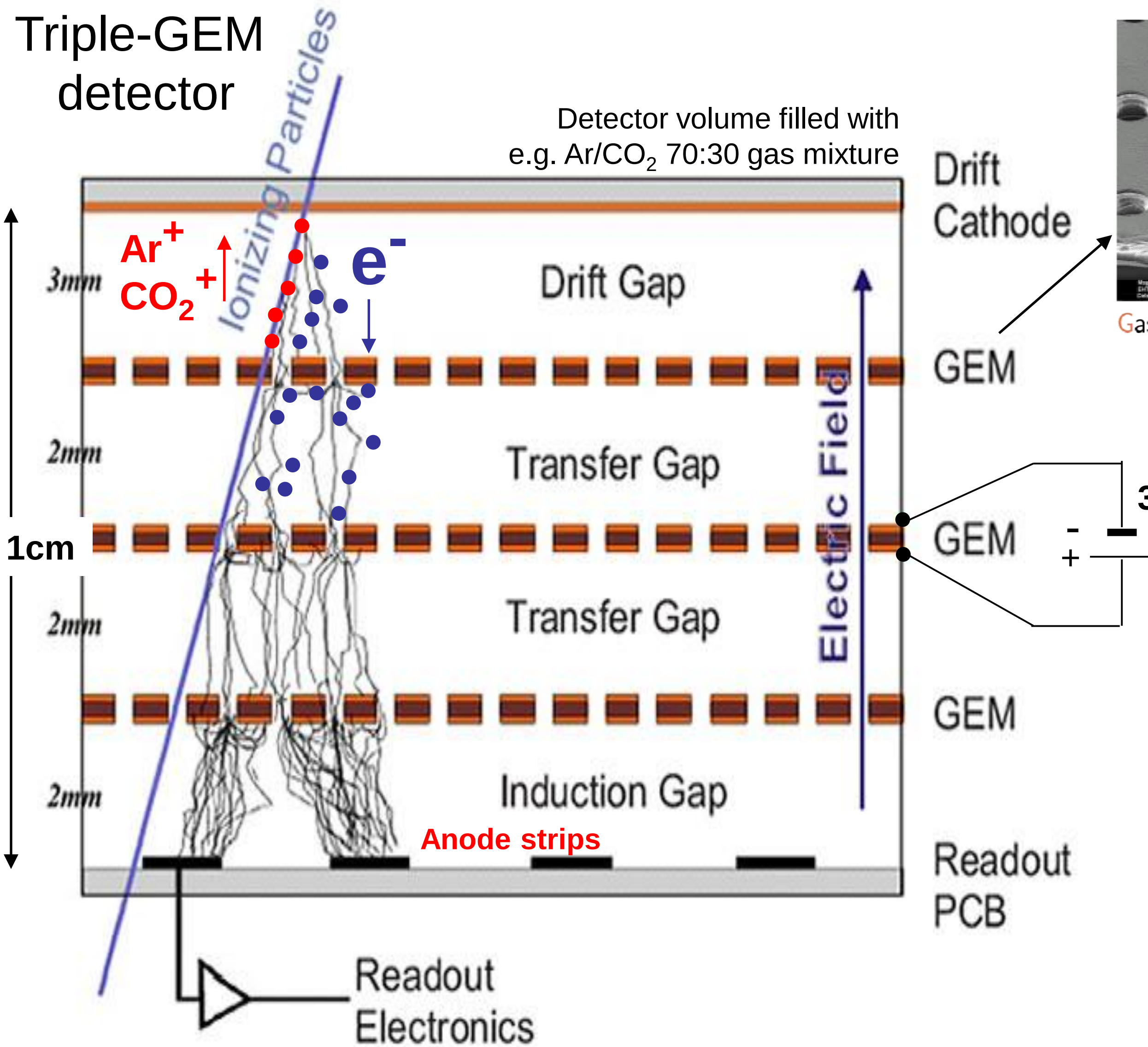
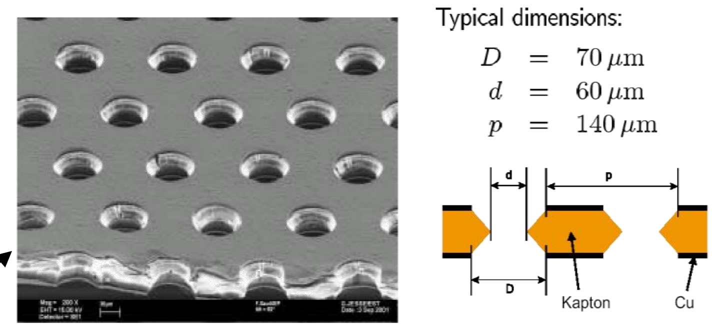
Outline

- GEM principle
- Large-area GEMs in experiments
    - EIC detectors
    - CMS forward muon upgrade
- **R&D on large-area GEMs for EIC**
    - Construction techniques
    - Prototype designs and performances
- Outlook

GEM Principle

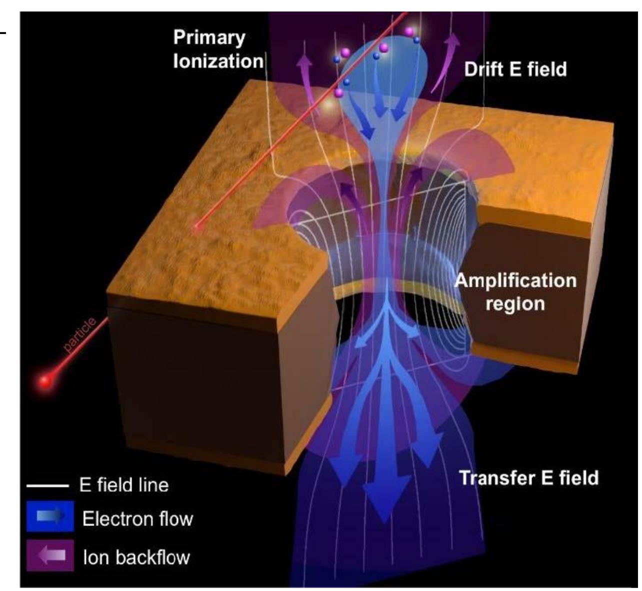




Gas Electron Multiplier [F. Sauli, NIM A386, 531 (1997)]

Micro-pattern gas detector (MPGD)

300 – 500 V (on each GEM)



CMS GEM upgrade TDR

Large-area GEM Uses

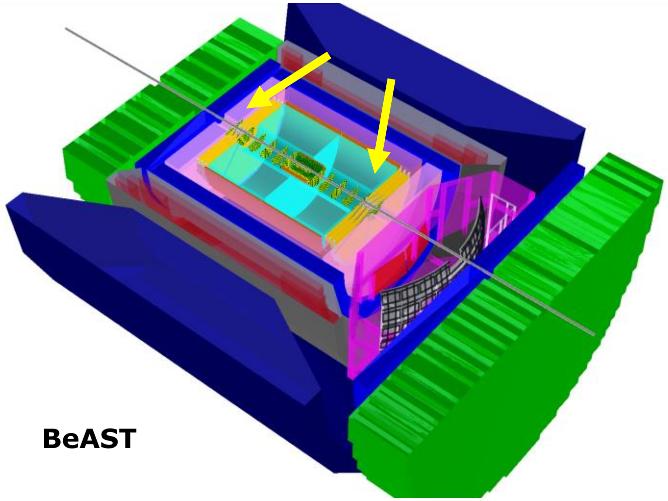
Examples in Nuclear and High Energy Physics:

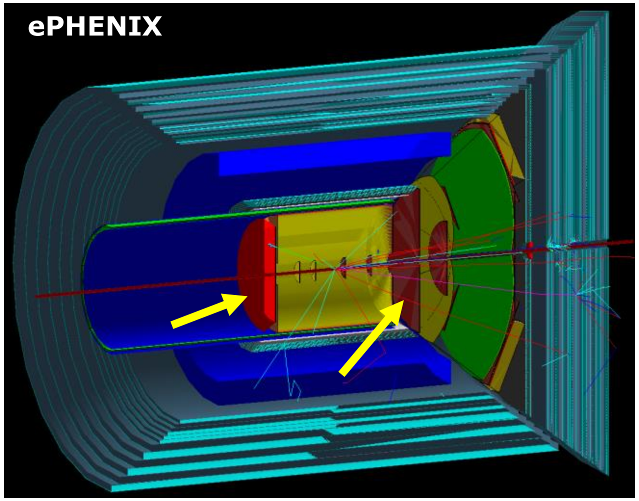
- ALICE
  - *TPC upgrade*
- CMS
  - *Forward muon upgrade*
- PRad
  - *XY tagger for calorimeter*
- Super Big Bite
  - *Main tracking*
- EIC detectors
  - *Forward tracking*

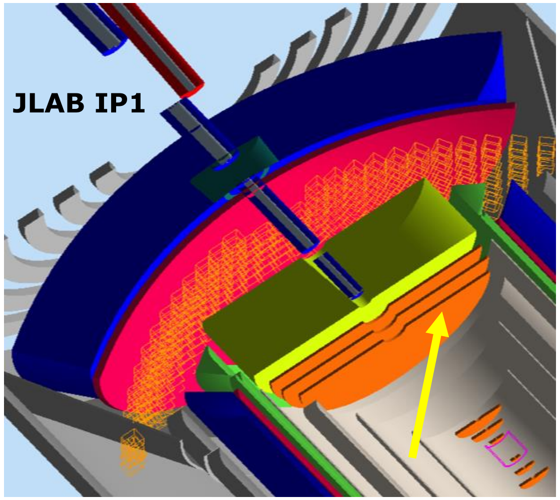
GEMs are usually considered "large" if they are ≥ 1m long.

Large GEMs for EIC Detectors

All proposed EIC detector concepts feature a form of large GEM tracker at forward and backward rapidities:







R&D effort dedicated to EIC forward tracking since 2011:

Florida Tech & U. Virginia (eRD6), Temple U. (eRD3)

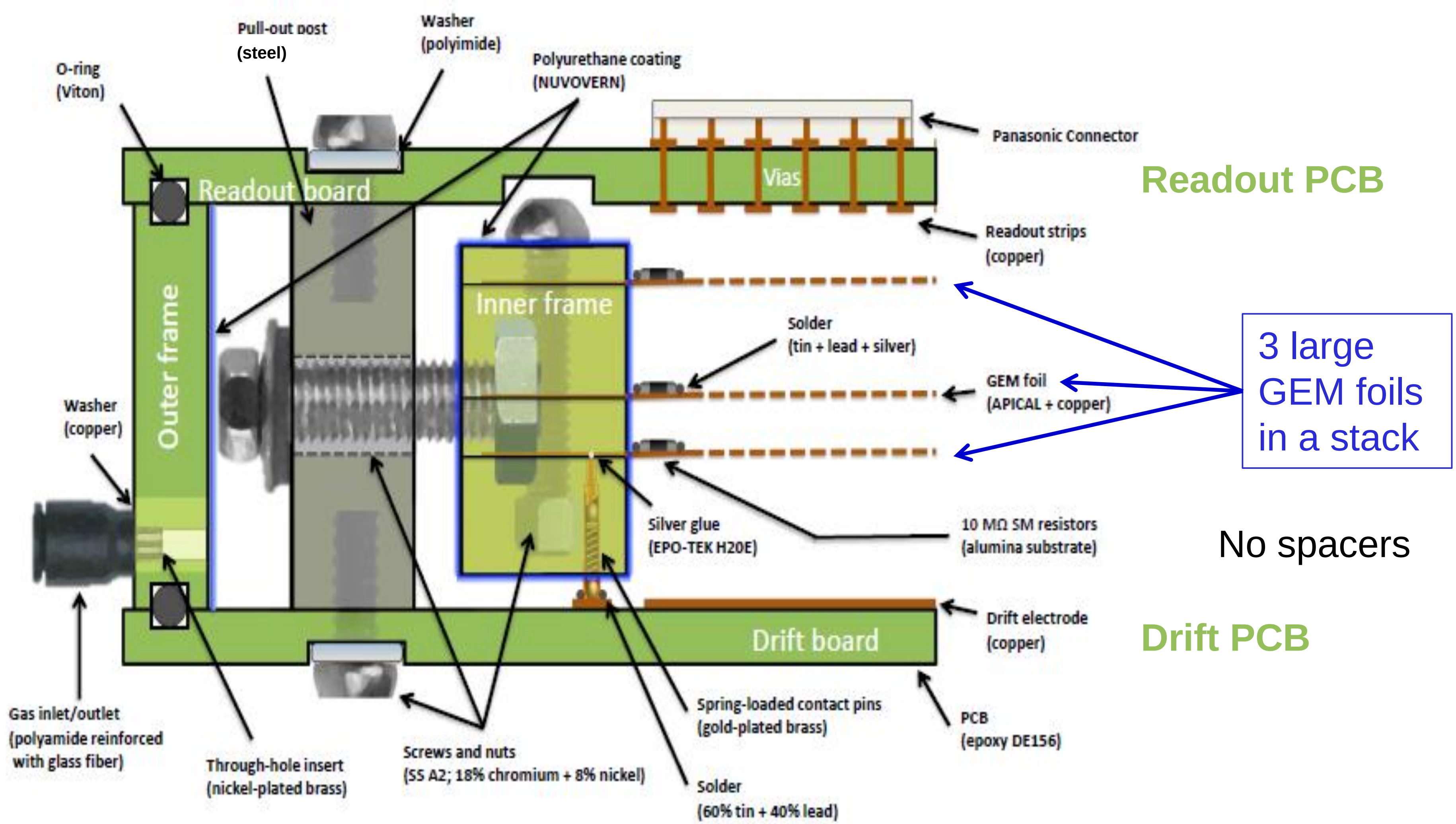
CMS Forward Muon Upgrade

Large GEMs were originally developed at CERN for the CMS forward muon upgrade project:

- **R&D program 2009-17** (with Fl. Tech participation)
  - Mastering of single-mask etching of Cu-Kapton base material made GEMs larger than ~ 30 cm × 30 cm feasible
  - Mechanical stretching and assembly of GEM foils makes internal spacers obsolete & allows re-opening of detector if needed (no gluing).
  - Ten full-size GEM detectors installed in 2017 (slice test)
- **Technical Design Report** for GEM upgrade in first muon station for High-Lumi. LHC approved 9/2015
- Currently preparing **mass production** of 160 GEM detectors & **second TDR** for two other muon stations

CMS GEM – Mechanical Construction

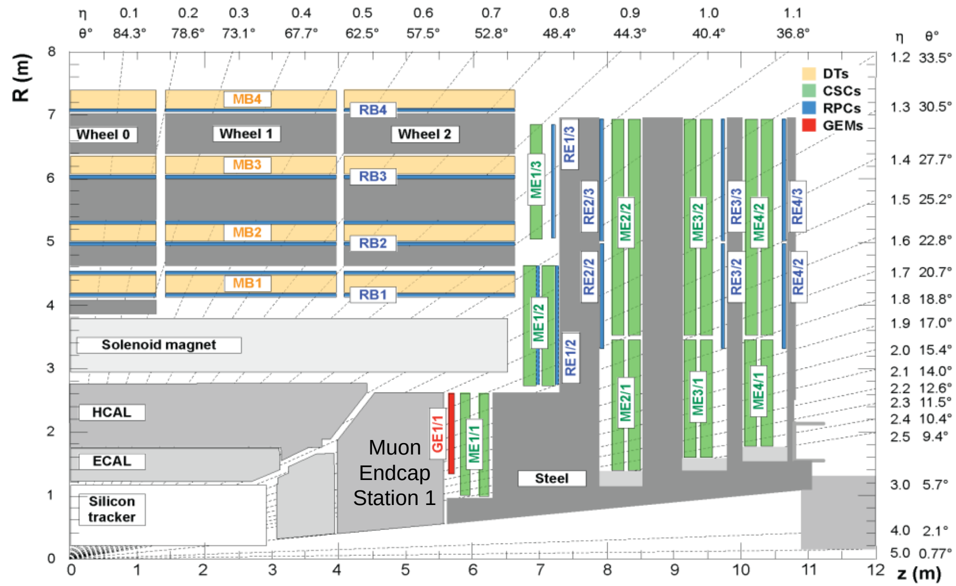
Purely mechanical assembly and GEM foil stretching:

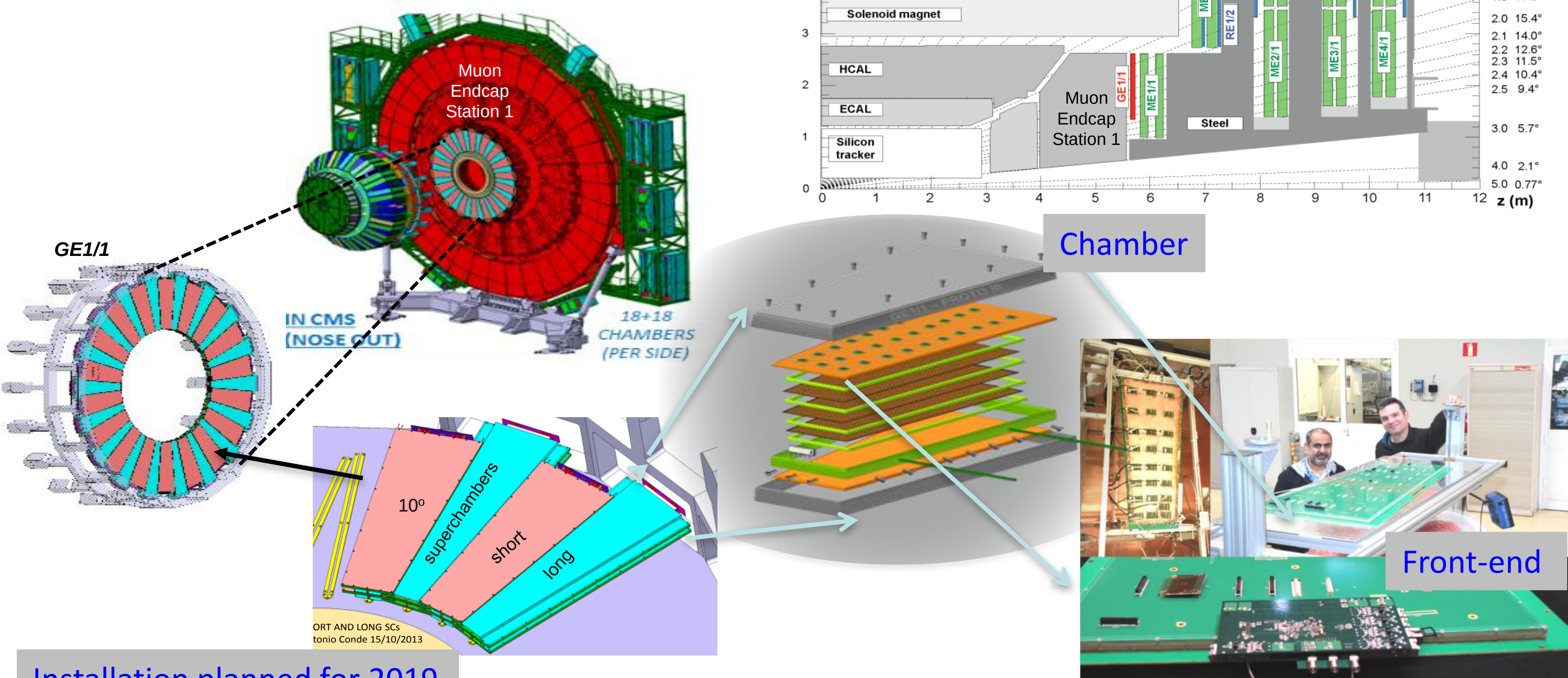


CMS GEM TDR (CERN LHCC-2015-012)

CMS GEM Upgrade

- *"GE1/1" GEM subsystem in region 1.5 < |η| <2.2*
- *10^0 trapezoidal triple-GEM Superchambers (2 ch.)*
- *Long and short versions (1.5 or 1.6 < |η| <2.2)*
- *36 superchambers in each endcap*





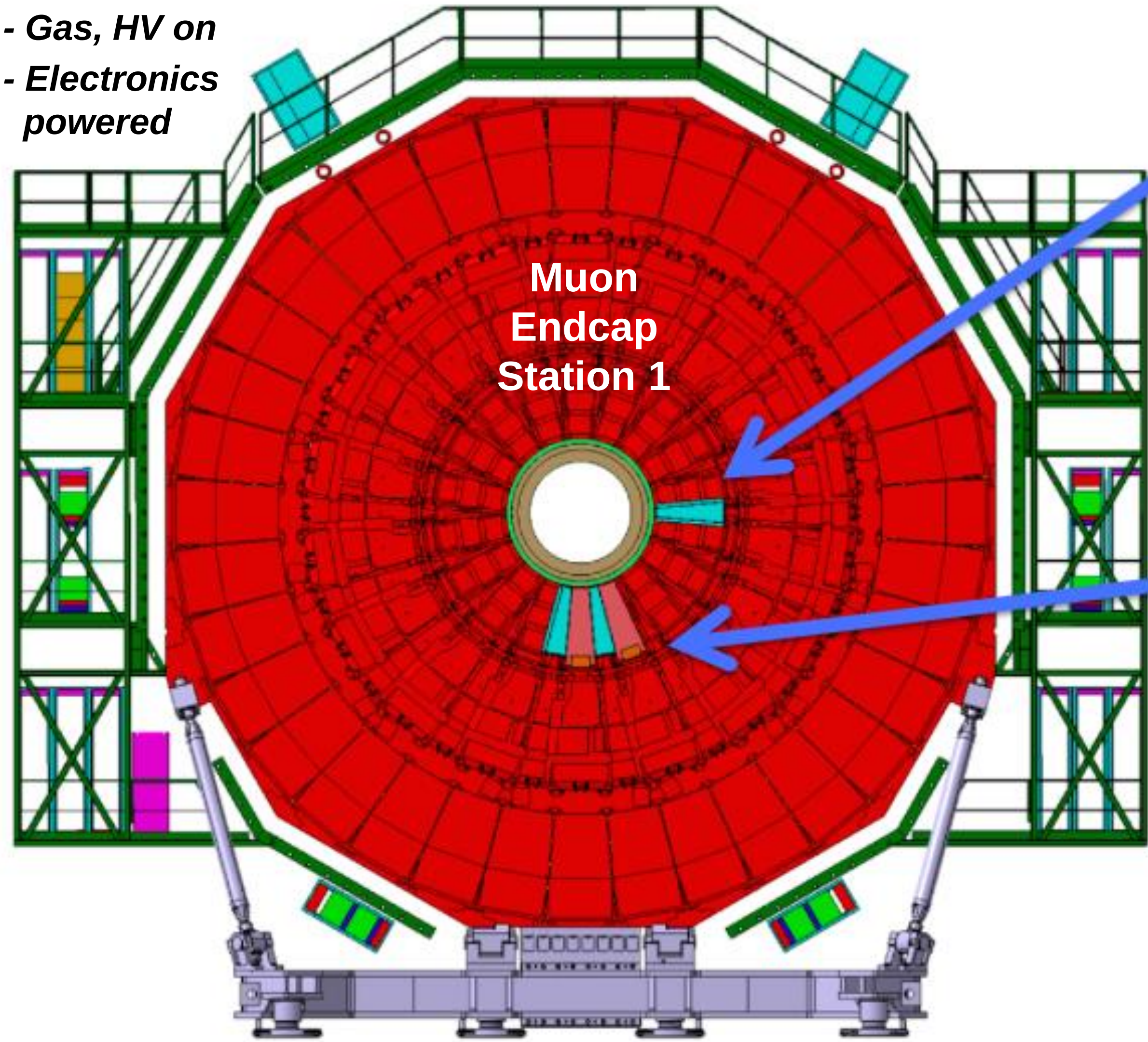
Installation planned for 2019

CMS GEM Slice Test Installation

Commissioning currently ongoing:

- ***Gas, HV on***
- ***Electronics powered***

January 2017

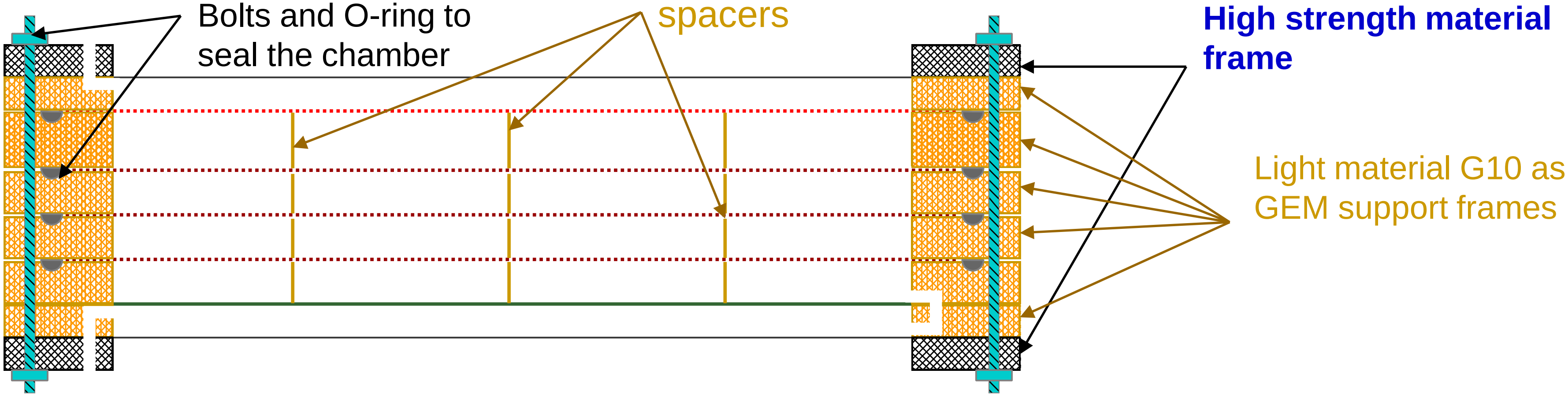


EIC GEM R&D: Construction

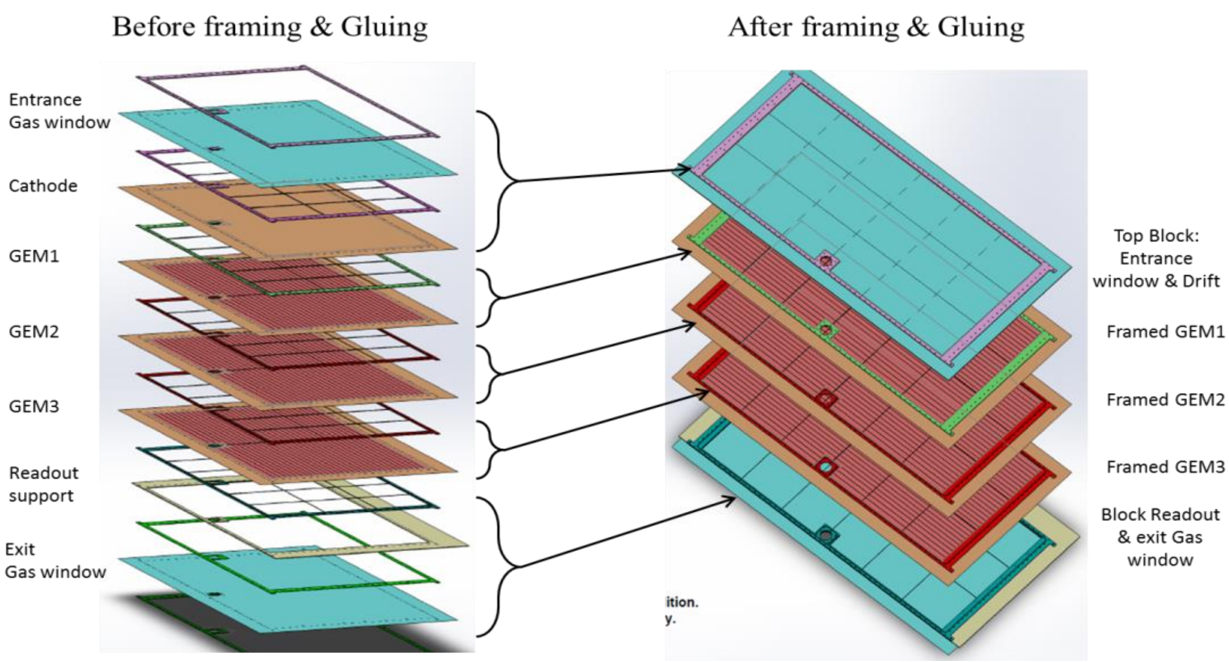
The three eRD3/6 FT groups are investigating **different detector construction techniques**:

- Constructing detector purely mechanically & without any spacers as in CMS (Florida Tech)
- Gluing stretched foils to FR4 spacer frames that are then mechanically assembled (U. Va.)
- Gluing entire detector and inserting kapton rings between GEMs as spacers (Temple)

Assembly with Bolted Spacer Frames (U. Va.)



Example: Exploded 3D view of PRad GEM design

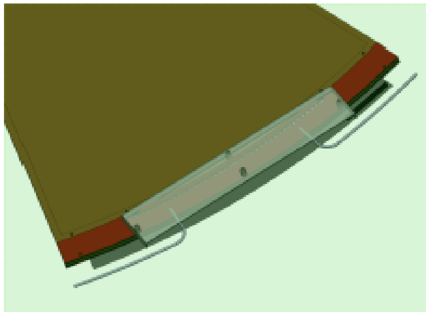


Chamber's characteristics

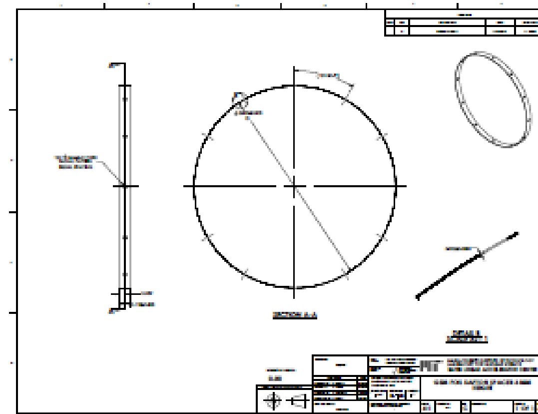
- Low material in active area
- No honey comb support but keep spacers
- Light material for GEM frames
- High strength material for external support frames
- Bolts & O-ring to seal the chambers

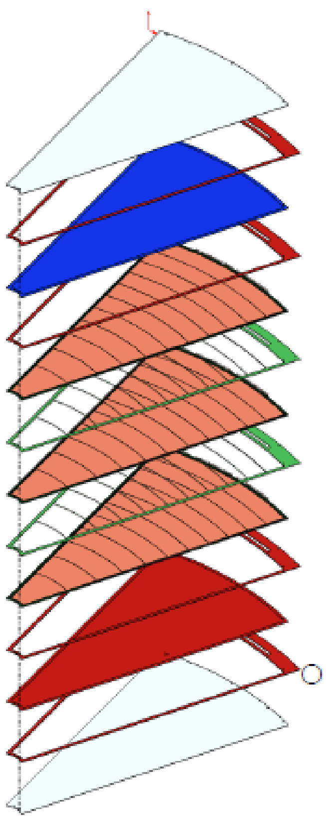
Courtesy Kondo Gnanvo, U.Va

Assembly with Glued Frames (Temple)

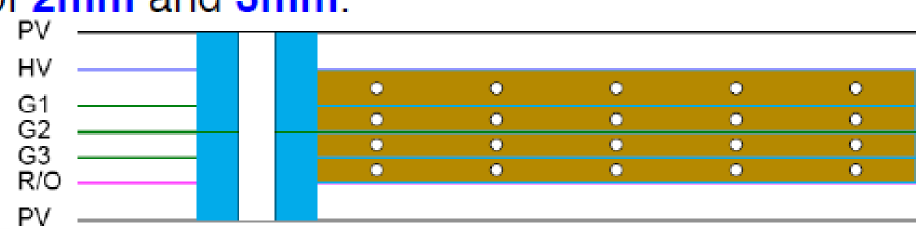


- **Temple** will assemble their EIC triple-GEM prototypes by:
  - **Gluing** the foils to the frames.
  - Forming the GEM stack by **gluing** the frames.
- This method **avoids** having to use bolts to keep the stack together.
- In order to help alleviate dead material, **Kapton rings** are being investigated to be used to separate the GEM layers rather than spacer grids. Spacer grids will be used if Kapton rings don't work.
- **Kapton rings**:
  - **Perforated** walls to allow for gas flow
  - Inner diameter of **50.8 mm**.
  - Wall thickness of **0.127 mm**.
  - Cut into lengths of **2mm** and **3mm**.





- Designed to have all HV, FE, and gas connections on **outer radius**.



EIC GEM R&D: Readout

The three eRD3/6 FT groups are investigating also **different signal readout techniques**:

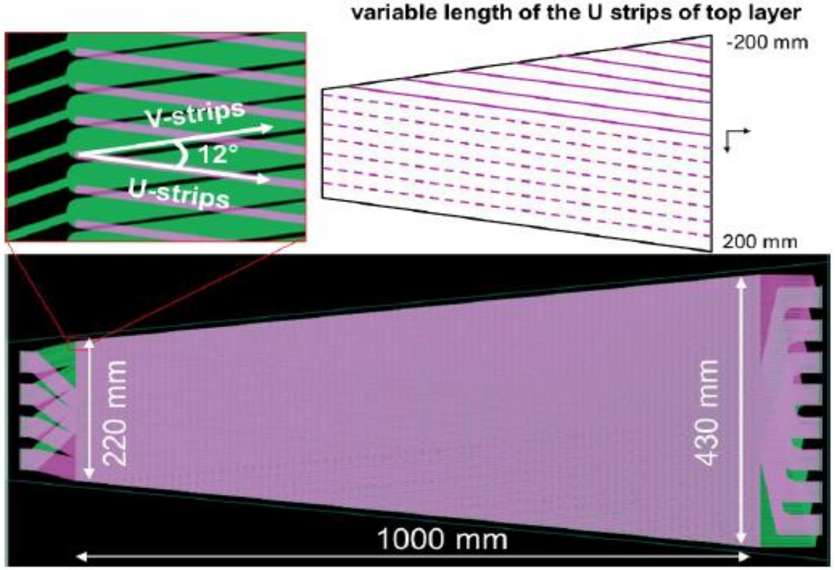
- 2D-readout with **U-V strips** (U. Va.)
- 2D-readout with **R-φ readout strips** (Temple)
- 1D-readout with **radial zigzag strips** that minimizes the number of strips and electronic channels to minimize cost while maintaining good spatial resolution (Florida Tech)

First U-V Readout Prototype (U. Va.)

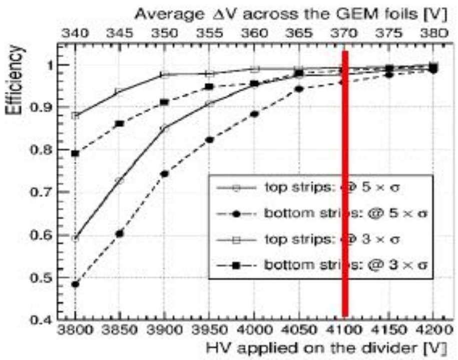
UVa EIC-FT-GEM proto I

- Trapezoid shape 1-m long triple-GEM (3-2-2-2): widths at the inner radius and outer radius equal to 23 cm and 44 cm respectively.
- Readout board: **2D flexible U-V strips** (COMPASS style) with a pitch of 550 µm, top layer (**140 µm, wide U-strips**) run parallel to one radial side of the detector and bottom layer (**490 µm, V-strips**) run parallel to the other side and a stereo-angle of **12 degree**

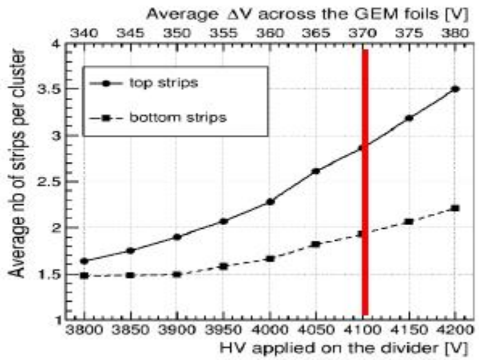
U-V strip Readout design



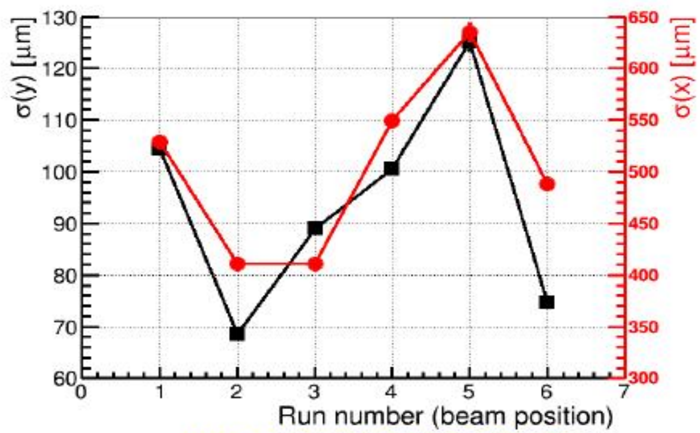
Efficiency



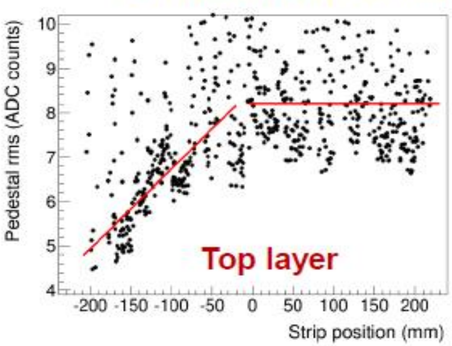
Mean cluster size

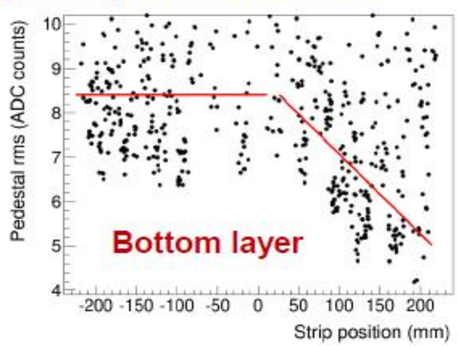


resolution in x (radial) and y (azimuthal)



Correlation between strip length and pedestal RMS noise





Courtesy Kondo Gnanvo, U. Va.

NIM A 808 (2016) 83-92

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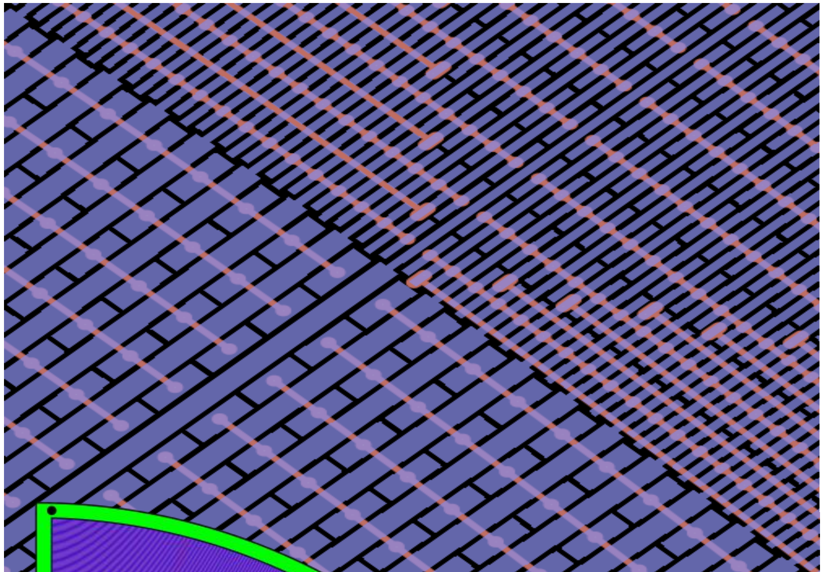
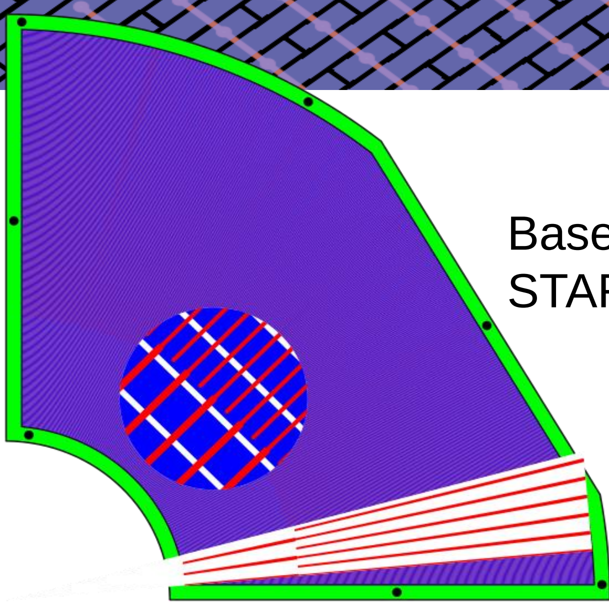
R,φ-strip Readout Design (Temple)

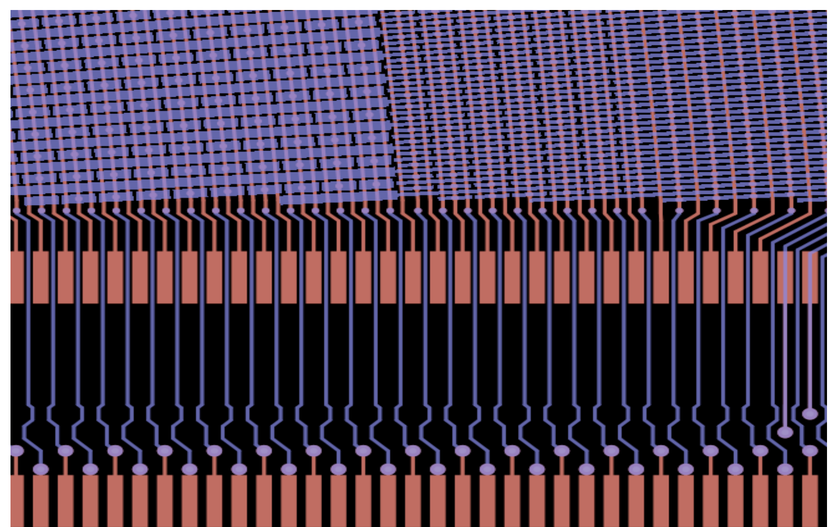
2D strips in R and φ coordinates. Implemented as strip-pad design with vias.



- **Active** layer is in **blue**:
  - **Lines** at constant **angle**.
  - **Pads** at constant **radius.**
- **Routing** layer in **orange**:
  - Each line is read out separately.
  - Pads at each radius are connected.
- **300-800 micron** pitch design.

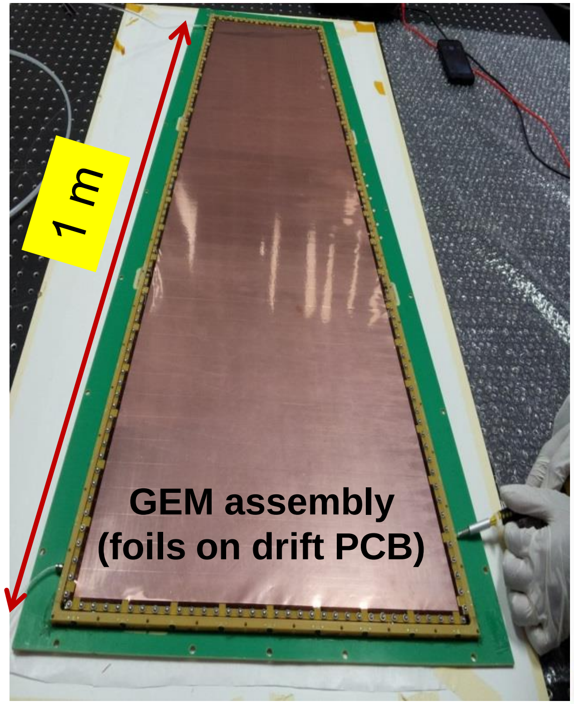


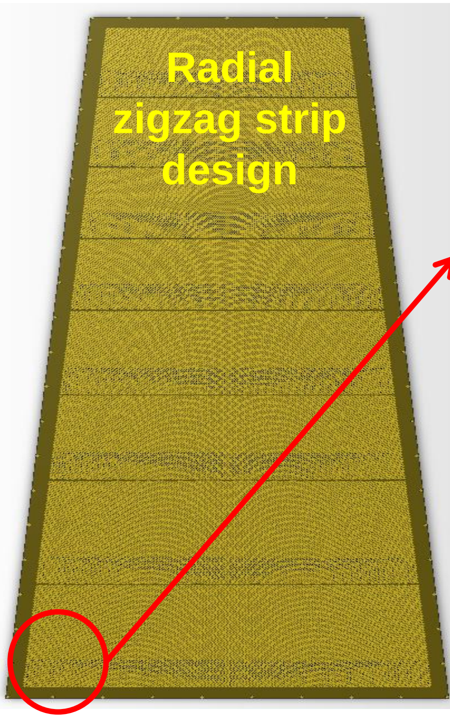
Based on STAR FGT

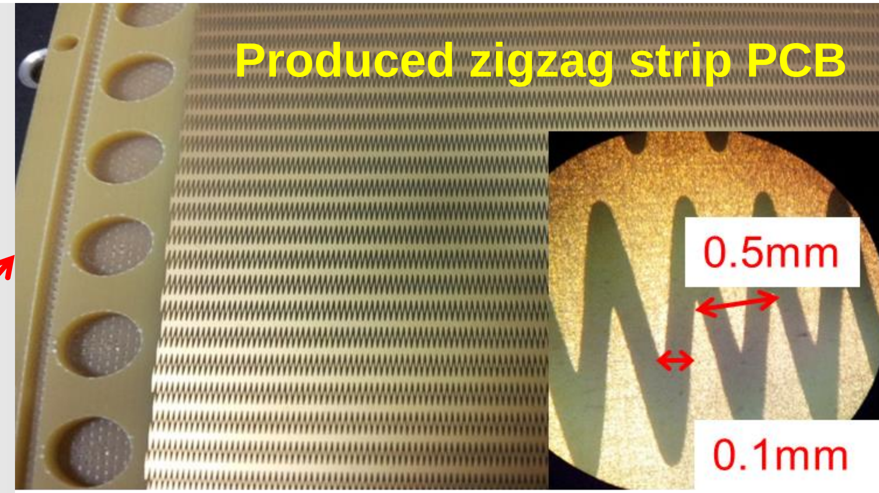


Courtesy Matt Posik, Temple U.

First Zigzag-strip Readout (FIT)







- CMS GEM detector equipped with a **readout with radial zigzag strips on a PCB**
- Number of strips and readout channels are **reduced by factor 3** relative to CMS readout
- Zigzag strips cover radial range R ≈ 1.6 - 2.6 m in 8 eta sectors
- Azimuthal strip angle pitch of 1.37 mrad; 128 strips per sector
- Prototype tested in beam at Fermilab (2013)
- **Performance: Angular resolution of ~193 µrad (362 µm at R = 1.88 m)**

NIM A 811 (2016) 30

EIC GEM R&D: Mult. Scattering

The three eRD3/6 FT groups are investigating methods to **reduce overall detector material**:

- Remove or reduce Cu on GEM foils (U. Va.)
- Replace solid drift and readout PCBs with carbon fiber composite frames (Florida Tech)

Reduces multiple scattering of tracks in the GEM detectors. Helps with:

- matching electron tracks to EM cluster
- seeding RICH ring reconstruction from incidence of hadron tracks on the RICH

EIC GEM R&D: Next Prototypes

- Adjust the GEM detector geometry to accommodate the **geometry of an actual EIC forward tracker**:

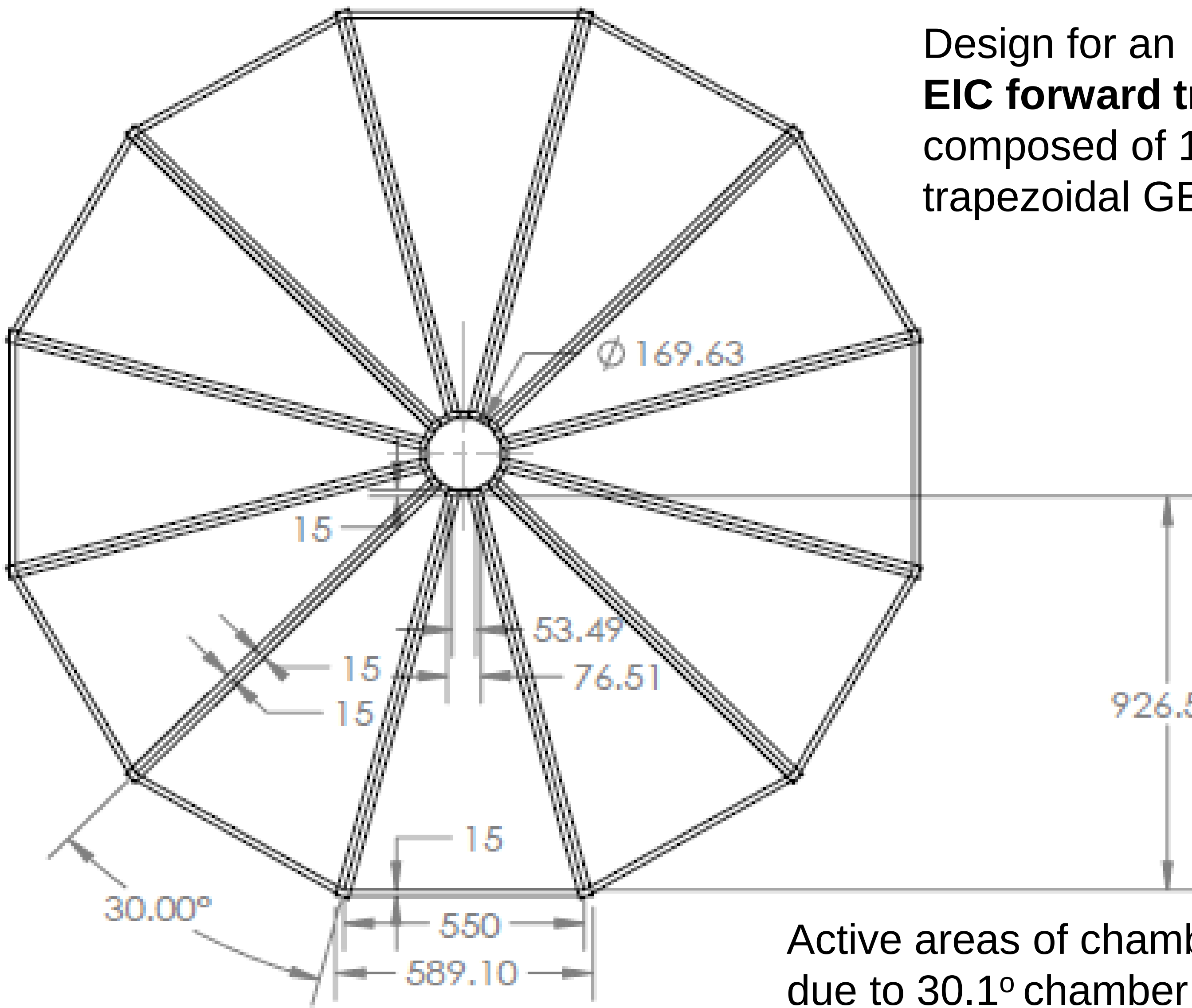
  $R = 8 – 98$ cm   radial coverage

  $\Delta\varphi = 30.1^{o}$ azimuthal coverage

- EIC R&D group designed a 1-m scale **common GEM foil**, which satisfies the requirements of all three assembly techniques to save cost

- 8 GEM foils were produced at CERN and delivered to Florida Tech and U. Va.

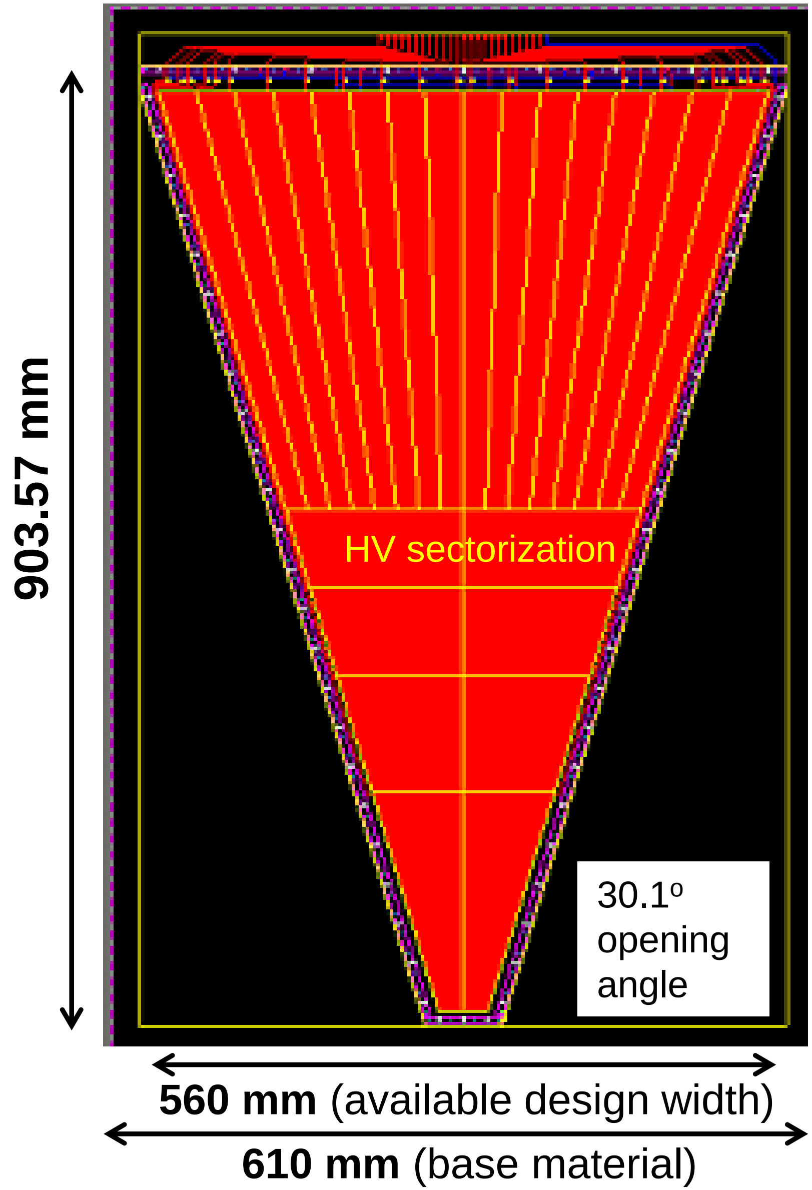
Overall EIC FT Geometry



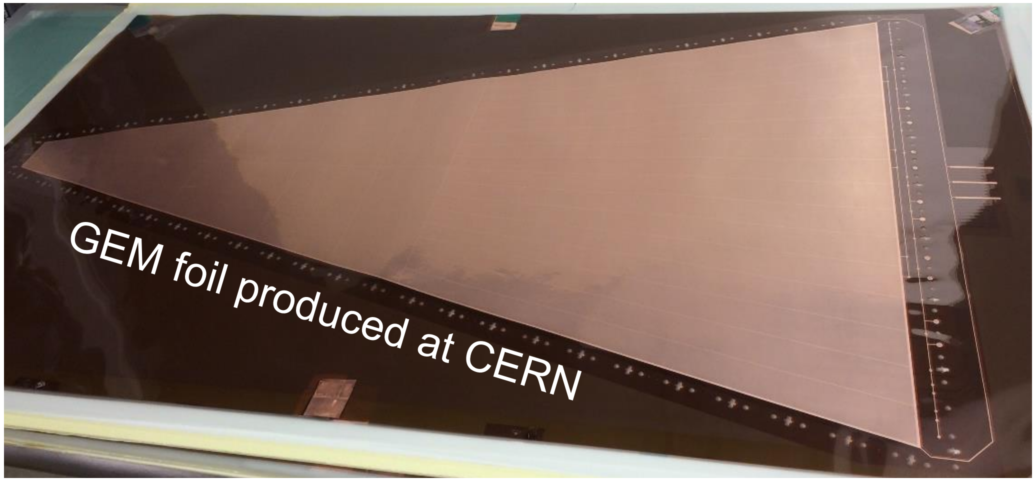
Design for an
EIC forward tracker disk
composed of 12 such
trapezoidal GEM detectors

Active areas of chambers overlap due to 30.1° chamber design.

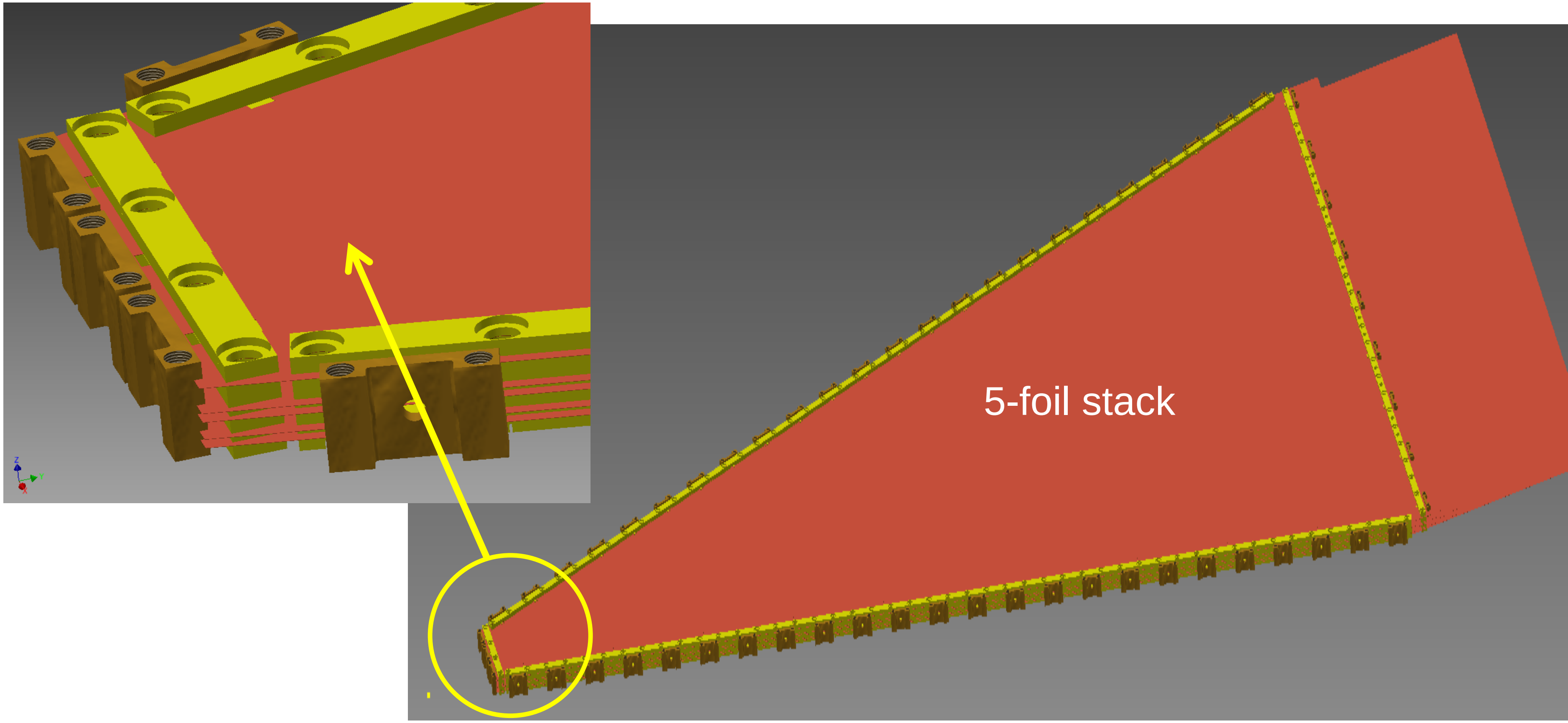
Common EIC GEM Foil Design



- Foil width (at the large R end) is limited to **560 mm** due to material limit of 610 mm
- 25 mm margins needed for foil production
- Trapezoid with a length of **903.57 mm**, widths of **43 mm** and **529 mm** (active area).
- Active area is divided into 8 HV sectors in R direction at inner R and 18 HV sectors in azimuthal directions at outer R. Reduces energy of any potential discharges.
- Each **HV sector is ~100 cm^2** and gaps between sectors are 0.1 mm.
- HV connections are made at wide end

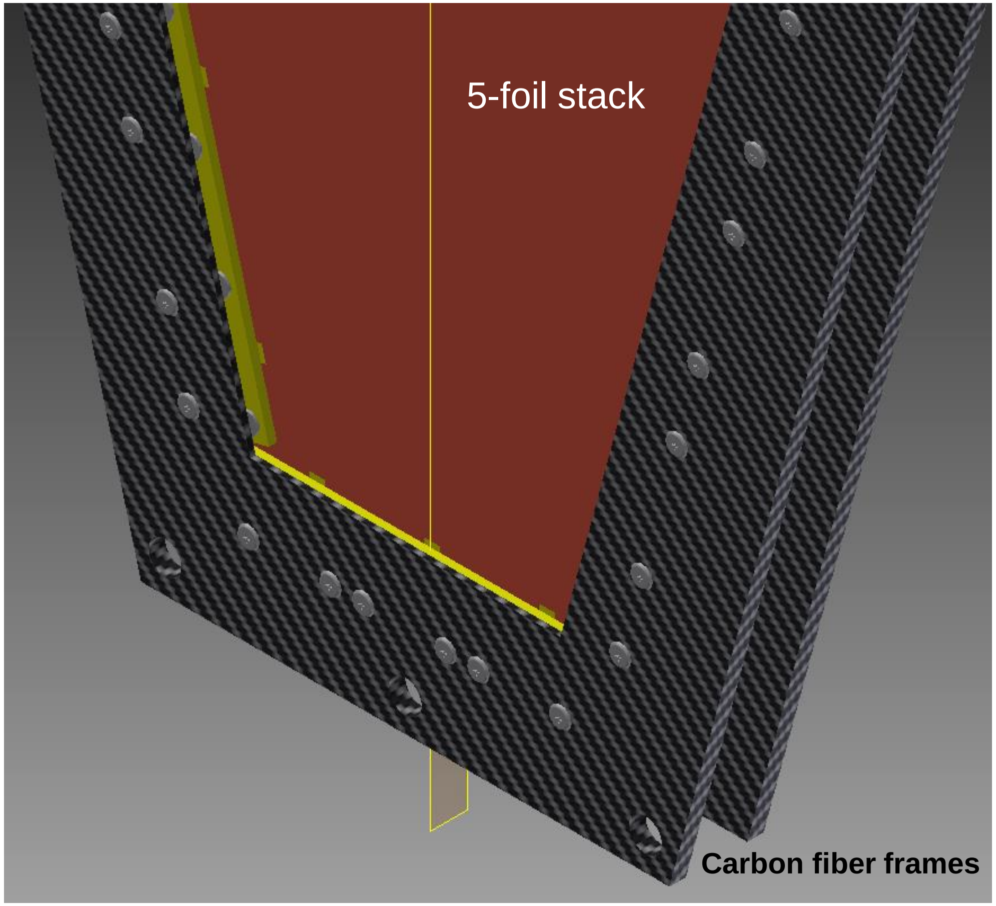


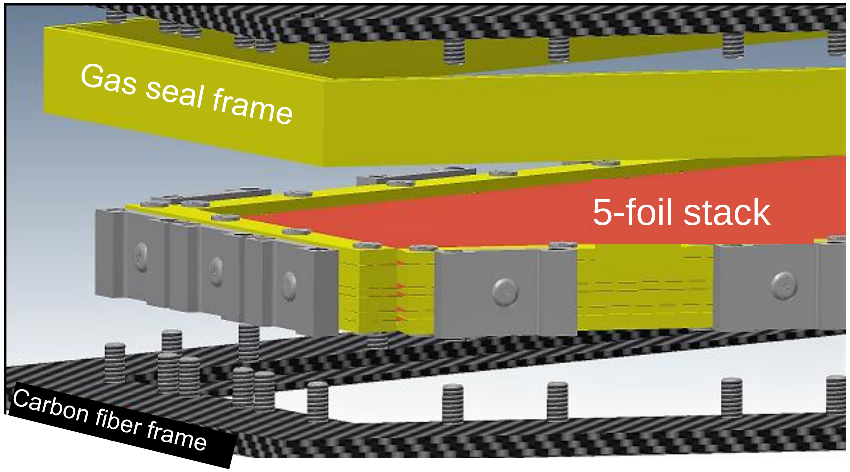
Modified Mechanical Stretching (FIT)



- **Stack of 5 foils** (3 GEM foils, 1 drift foil, and 1 readout foil)
- No spacers

Carbon Fiber Frames (FIT)



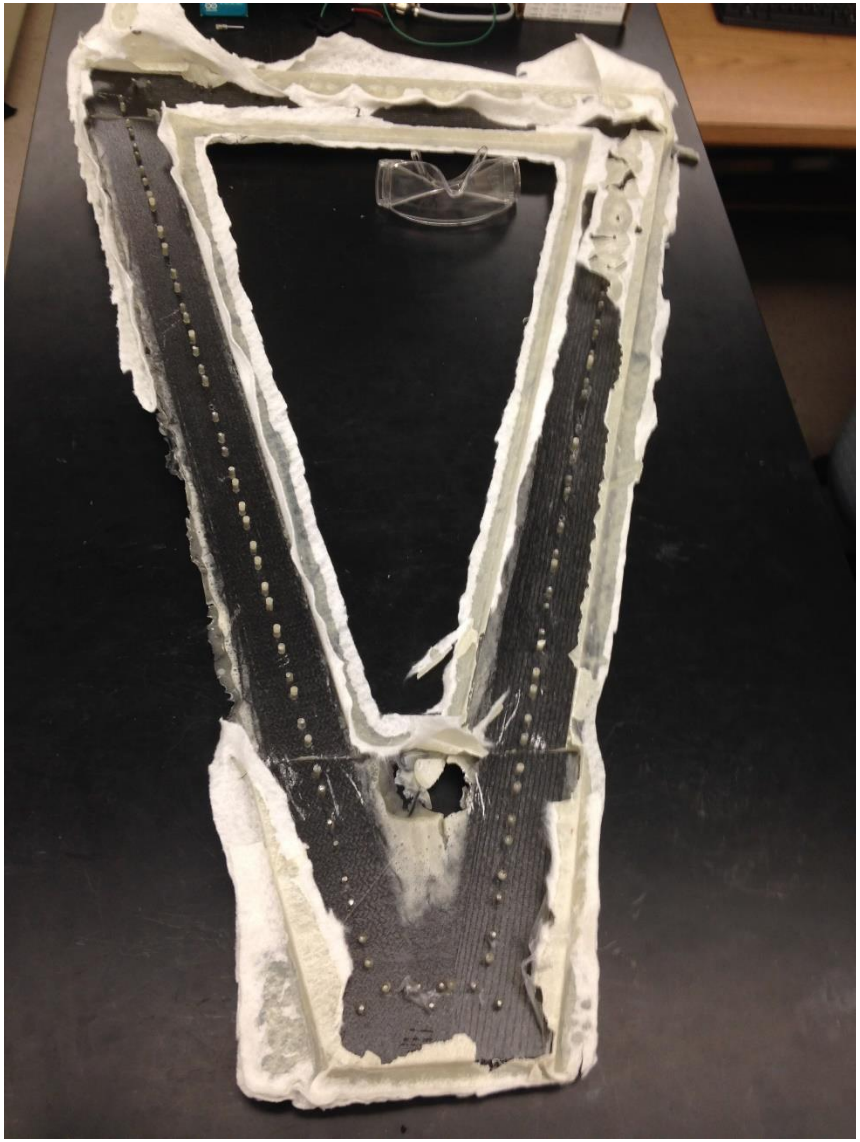


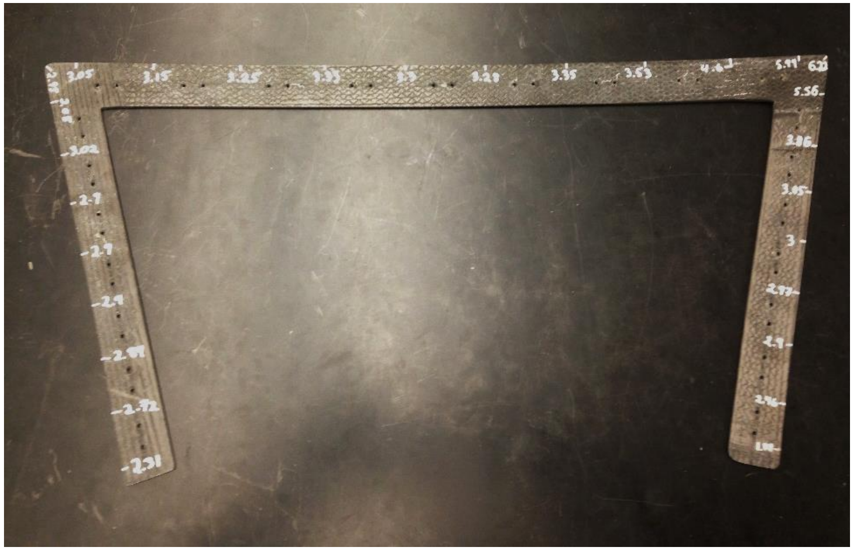
Exploded assembly view

Assembled detector

- Mechanical support structures are **outer frames with windows** (e.g. aluminized mylar foil, not shown here) instead of solid PCBs to reduce radiation length in the active area
- **Frames are made from carbon fiber composites** that have high strength to take up the tension from the stretched foils

CF Composite R&D (FIT)





Trimmed quarter-frame (test piece, 175 g)

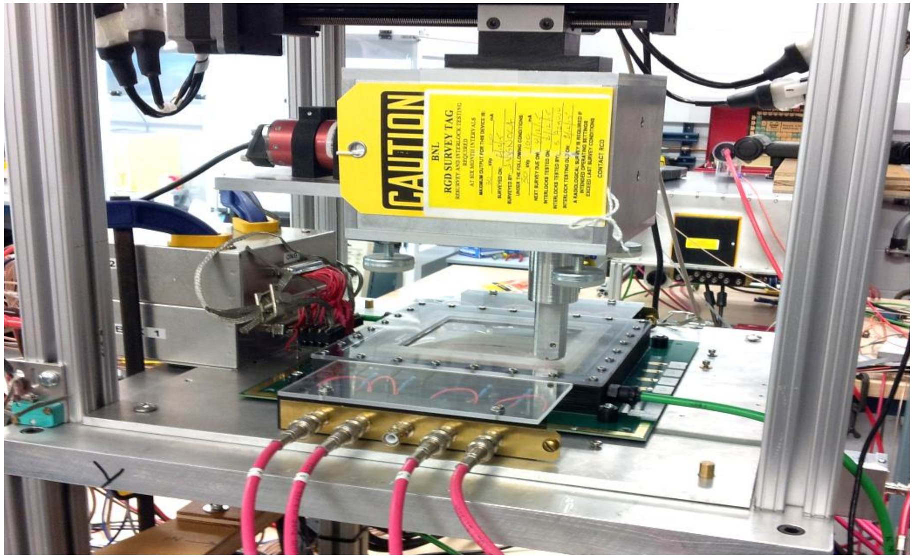
Carbon Fiber Composite:

- Araldite epoxy (AY103)
- Intermediate-modulus uni-directional carbon fiber ("IM7")
- 8 layers
- Produced in-house

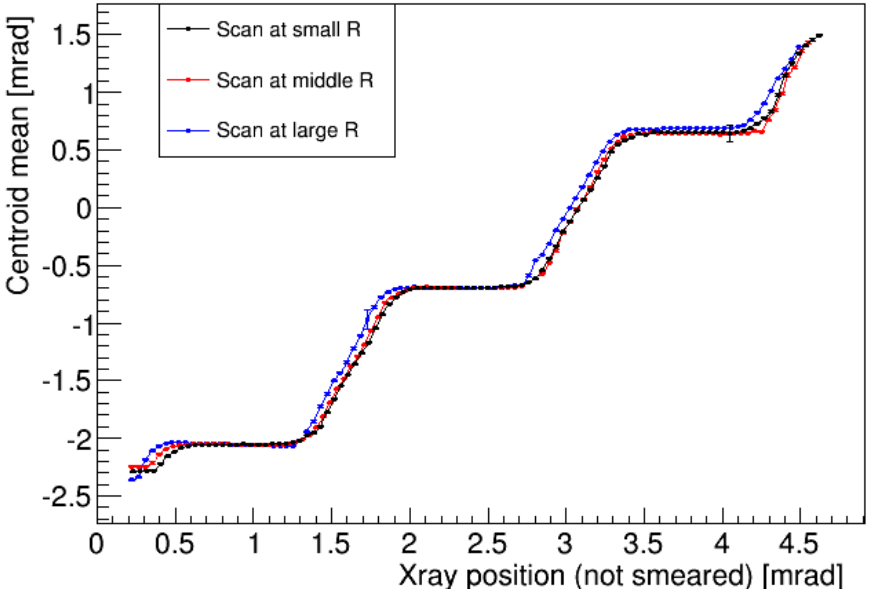
Raw full drift frame before trimming

Non-linearity of First Zigzag Readout

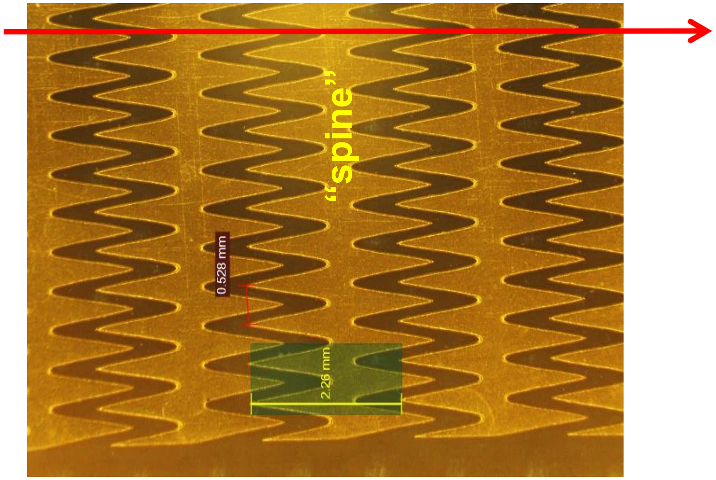
2D stage and highly collimated X-ray gun at BNL



Reconstructed position vs. X-ray position (azimuthal)



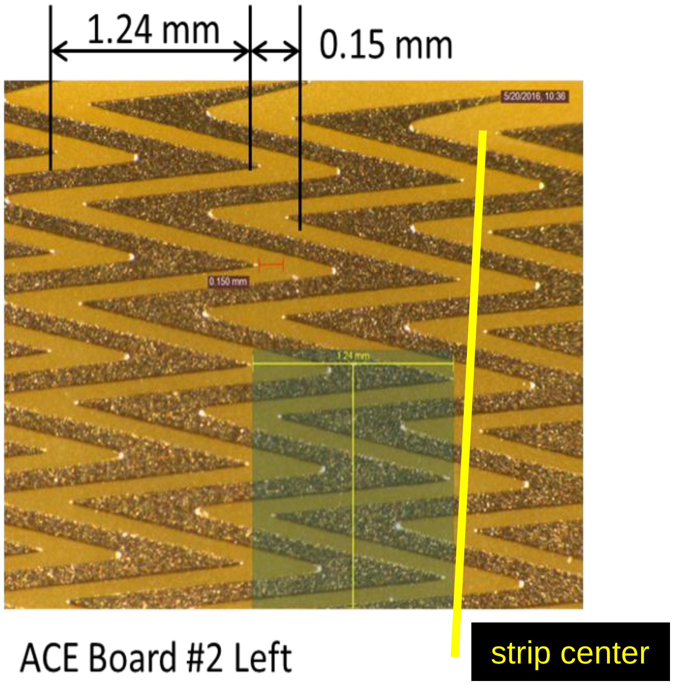
Scans across strips at 3 different radii



- **Overetching** of tips and **underetching** of valleys of zigzag strips creates "spines" along strip centers
- GEM avalanche induces signal only on single strip
- Without charge sharing among adjacent strips:
  - Readout is insensitive to hit positions near the strip centers
  - Overall spatial response is non-linear
  - Spatial resolution degrades

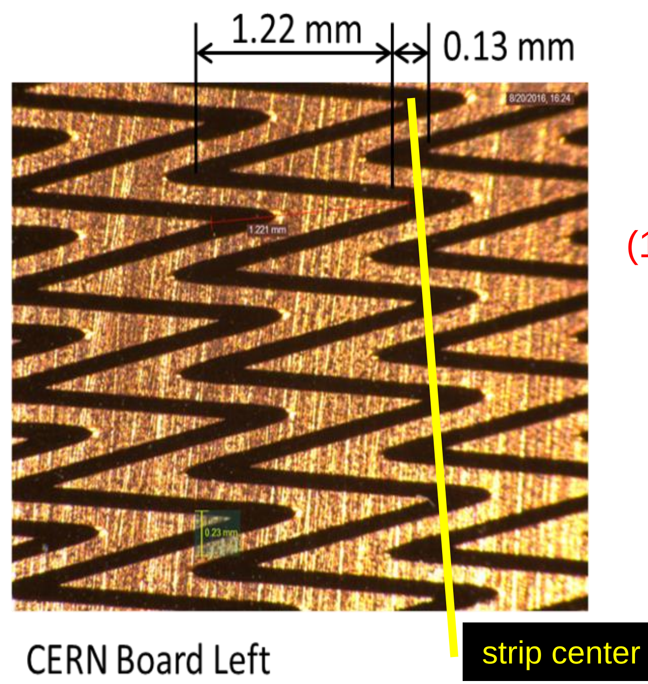
Zigzag strips interleave almost all the way to centers of both neighboring strips:

Industrial PCB
(10×10 cm^2)



ACE Board #2 Left
Interleaving: 1-(0.15/2)/1.24=**94%**
Copper thickness: 9 µm (1/4 oz)

CERN Foil
(10×10 cm^2)



CERN Board Left
Interleaving: 1-(0.13/2)/1.22=**95%**
Copper thickness: ~ 5 µm

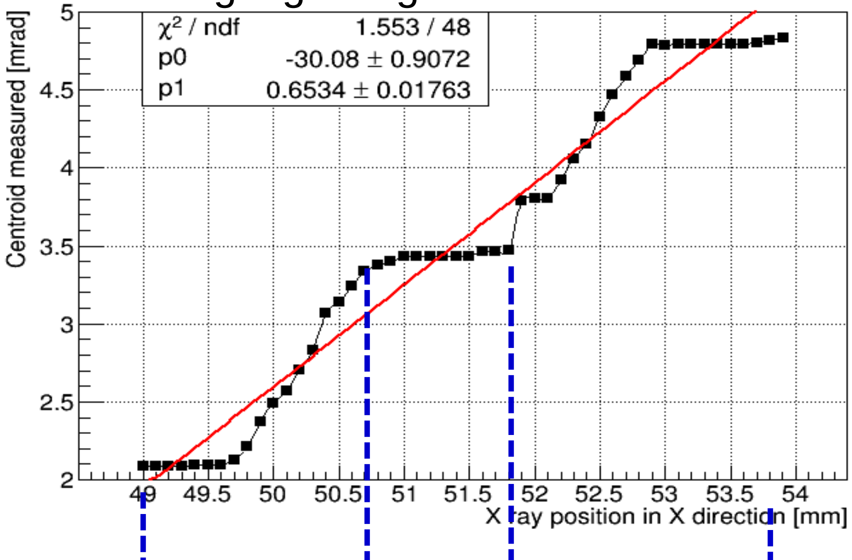
- The design **pushes the PCB manufacturing limit** since spaces are below 3 mils (76 um)
- Produced a **foil readout board at CERN** to verify that there is no problem with producing high-quality zigzag strips on a large-area kapton foil at CERN
- Same design is implemented on large 1-m zigzag readout foil being produced at CERN

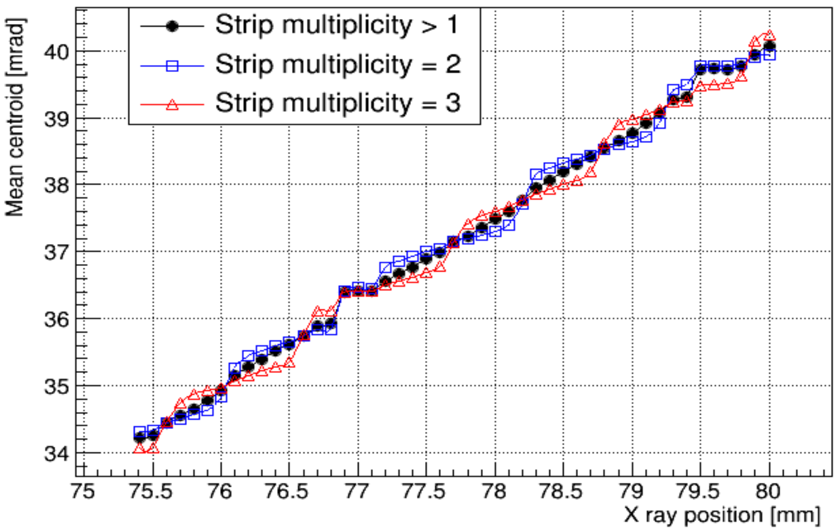
Much Improved Linearity

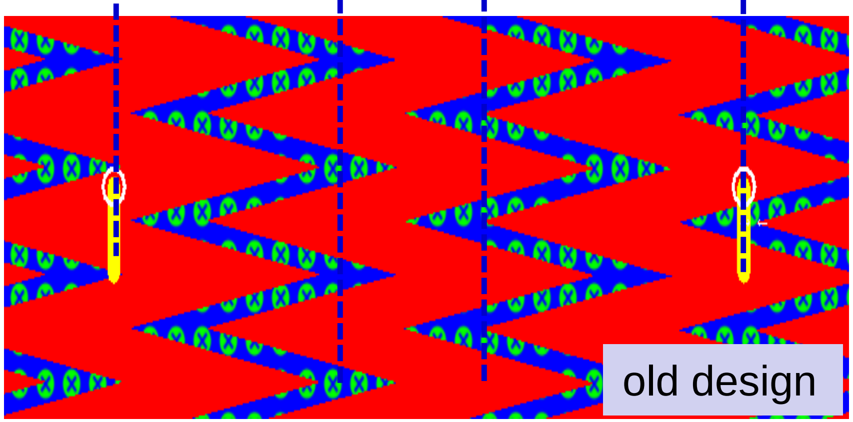
Mean centroid measurement vs. X ray position (scan across strips)

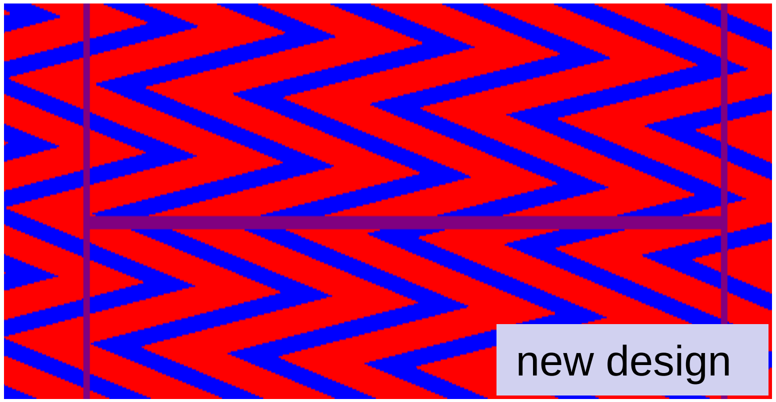
Previous zigzag design

New board (same angle pitch)









Flat regions insensitive to hit positions.

- Linear response over whole range
- > 95% events fire 2 or 3 strips.

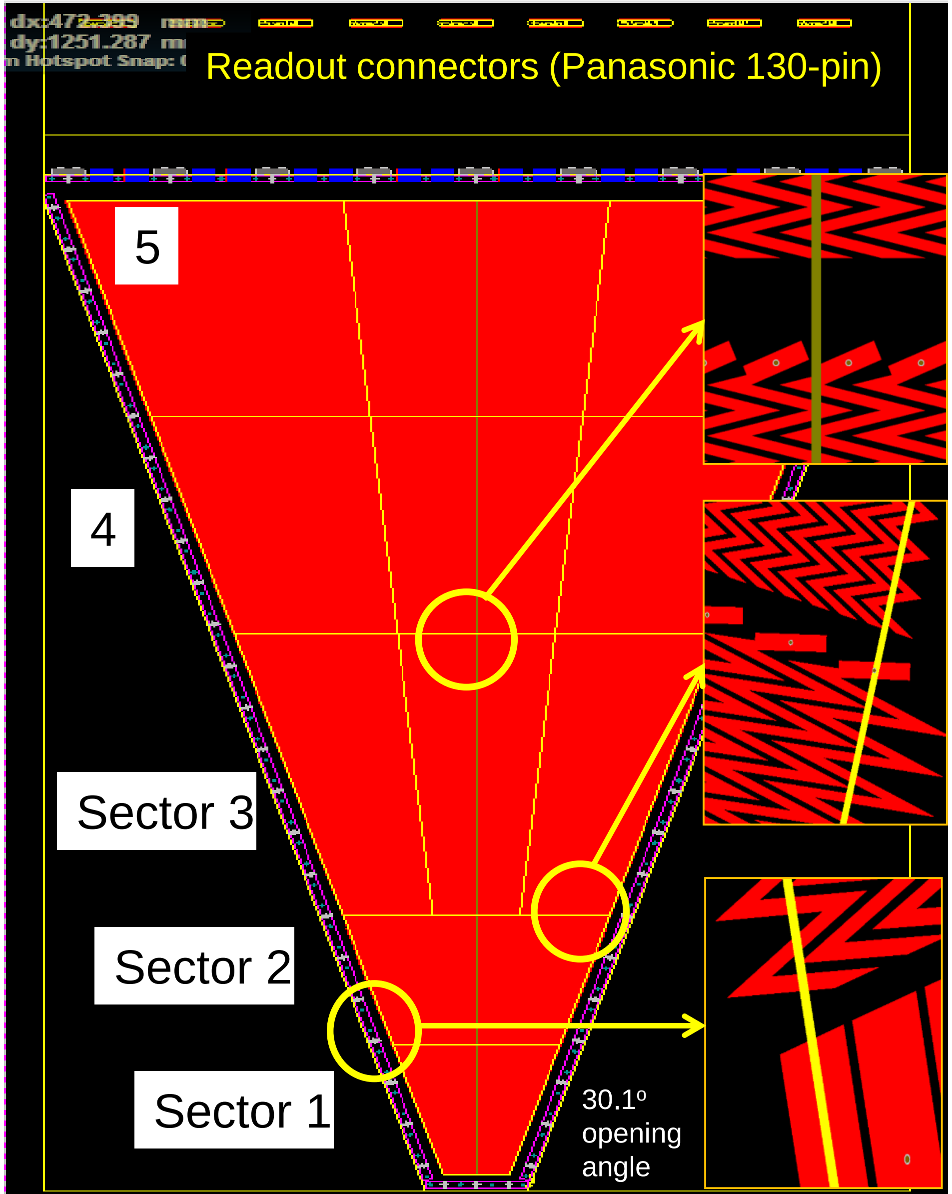
Spatial Resolution

Measured resolutions for improved zigzag-strip readout boards:

Spatial resolution (µrad / µm)	V_{drift} (V)	Approx. gas gain	Strips with angle pitch 4.14 mrad, r ≈ 229 mm			Strips with angle pitch 1.37 mrad, r ≈ 784 mm		
			2-strip clusters	3-strip clusters	2 & 3-strip clusters	2-strip clusters	3-strip clusters	2 & 3-strip clusters
Industrial PCB	**3340**	**3000**	**288 / 66**	**480 / 110**	**384 / 88**	**57 / 45**	**97 / 76**	**84 / 66**
CERN foil	**3340**	**3000**	**397 / 91**	**393 / 90**	**397 / 91**	-	-	-
CERN foil	**3380**	**4000**	**-**	**-**	**-**	**57 / 45**	**92 / 72**	**71 / 56**
Previous PCB			-	-	-			193 µrad

Linear resolutions (well) below 100 µm

EIC Zigzag Readout Foil (FIT)



Sec. Nr.	Strip type	No. of strips	Angle pitch (mrad)	Sector Length (cm)
1	Straight	128	4.14	12
2	Zigzag	128	4.14	12
3	Zigzag	384 (3×128)	1.37	22
4	Zigzag	384	1.37	22
5	Zigzag	384	1.37	22

- **Adopt the improved zigzag strip design** but use straight strips in small innermost sector 1
- Divide readout into **5 main eta sections**
- Produce r/o on a foil material (<200 µm thickness) so that total material in detector is reduced
- Total **number of channels is 1152** (=128*9)
- Only 9 APV chips to read out the full detector
- Foil is a 2-layer design; signal routing from strips to connectors for APV front end was a challenge
- **Foil currently in production at CERN**
- Expect delivery by end of March 2017

Summary & Outlook

- Large-area GEM detectors have become quite popular with a diverse set of experiments

- **Active EIC forward GEM tracking R&D since 2011**
  - Conceptual design for full EIC FT disk
  - Built a common 30.1º GEM foil
  - Developing & testing different assembly methods and readout designs
  - Second round of full-size prototyping in progress
  - Planning tests with X-rays and possibly beam in 2017

- **EIC Forward Tracking R&D readily applicable to RHIC detectors for forward spin physics**

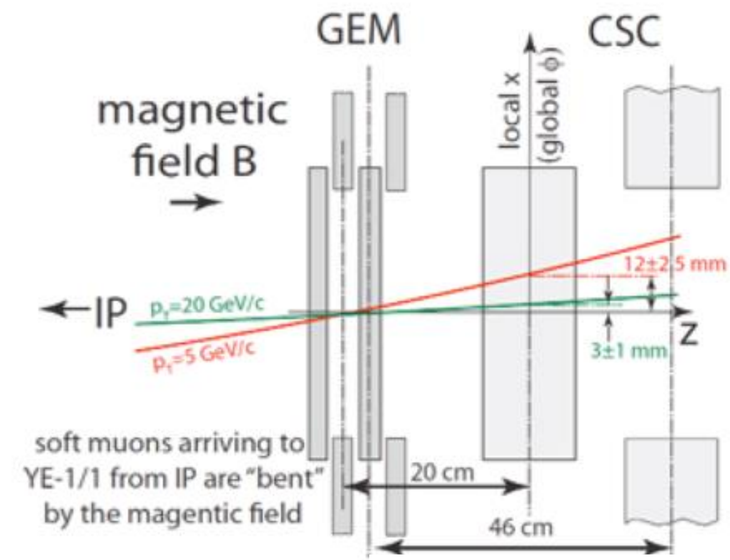
Thank you!

BACKUP

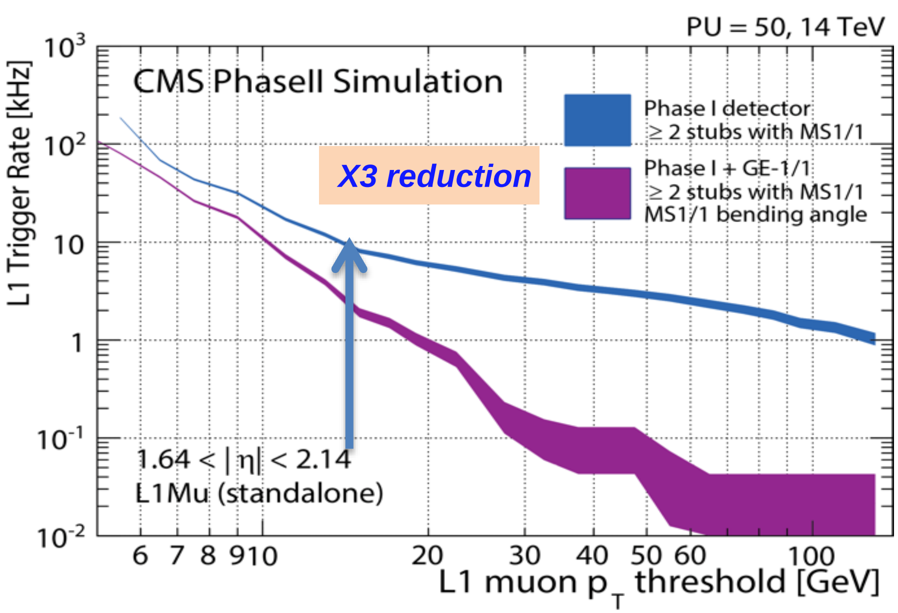
GE1/1: Muon Measurement

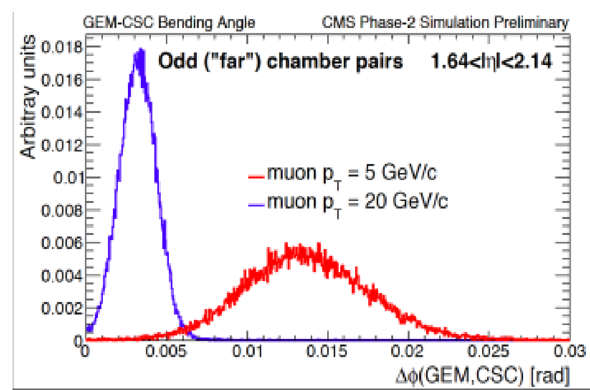
Florida Tech

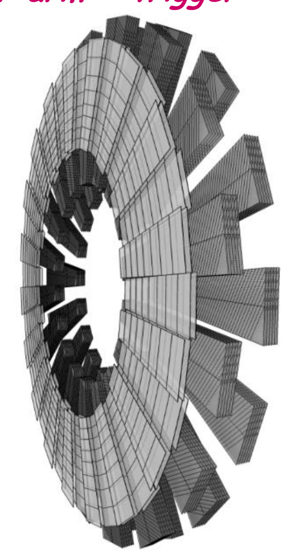
- GE1/1 creates a large lever arm with the CSC ME1/1 chambers
  - Enables precise measurement of muon direction
  - Much improved Level-1 trigger momentum resolution and lower rates in otherwise a problematic region of the detector



Lever arm - trigger



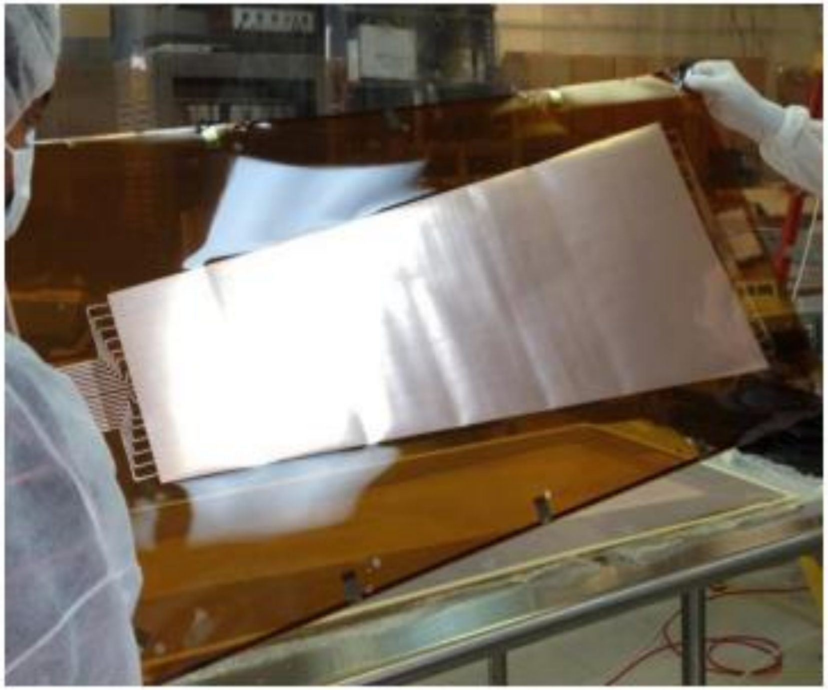


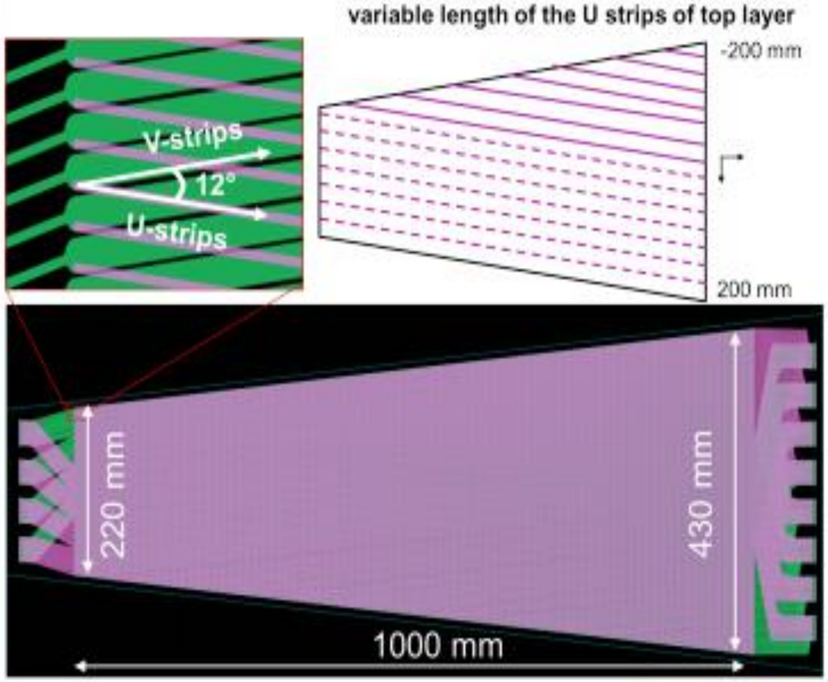


Maintain low p_T online threshold, keep < 5 kHz rate, high efficiency

First Iteration

- **The U. Va group** has assembled and tested a 1-m long triple-GEM detector equipped with 2D stereo angle (U-V) strips.
- Assembly method: **glue foils to frames that are held together to with screws**.
- Resolutions of 60 urad in azimuthal direction and better than 550 um in radial direction are achieved.

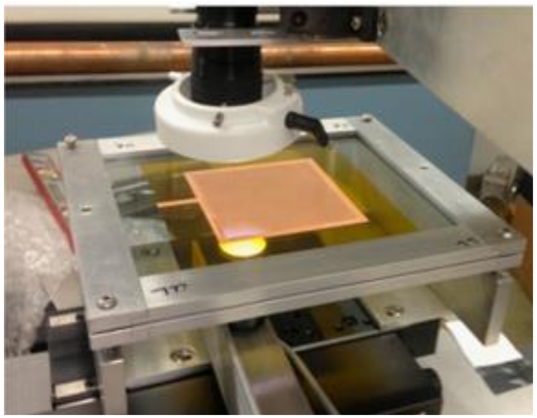


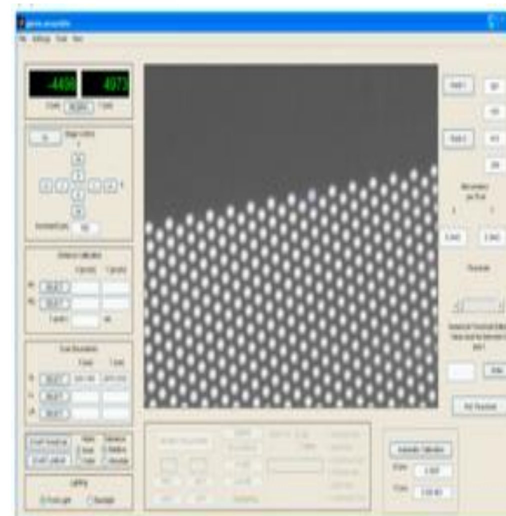


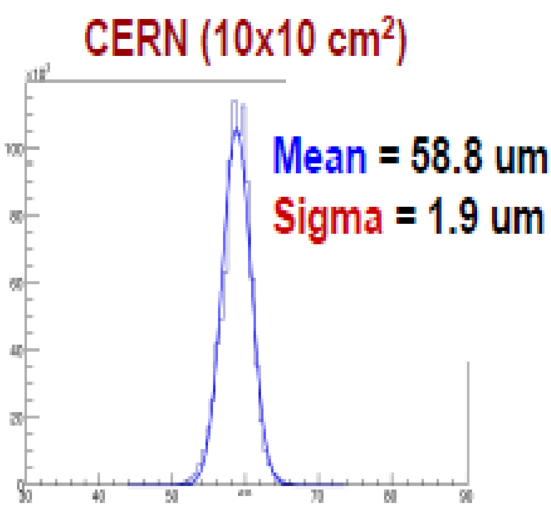
Ref.: NIM A 808 (2016) 83

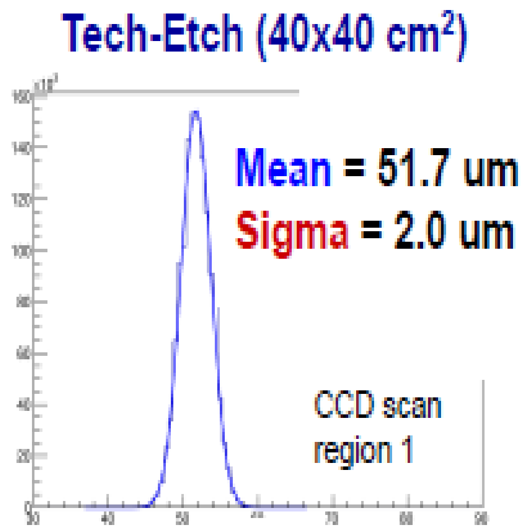
GEM foil scanning (Temple)

- Scanned 40 cm × 40 cm GEM foils from commercial supplier and small CERN foils with an automated CCD camera setup. Currently upgrading CCD scanner so that large GEM foils can also be scanned.







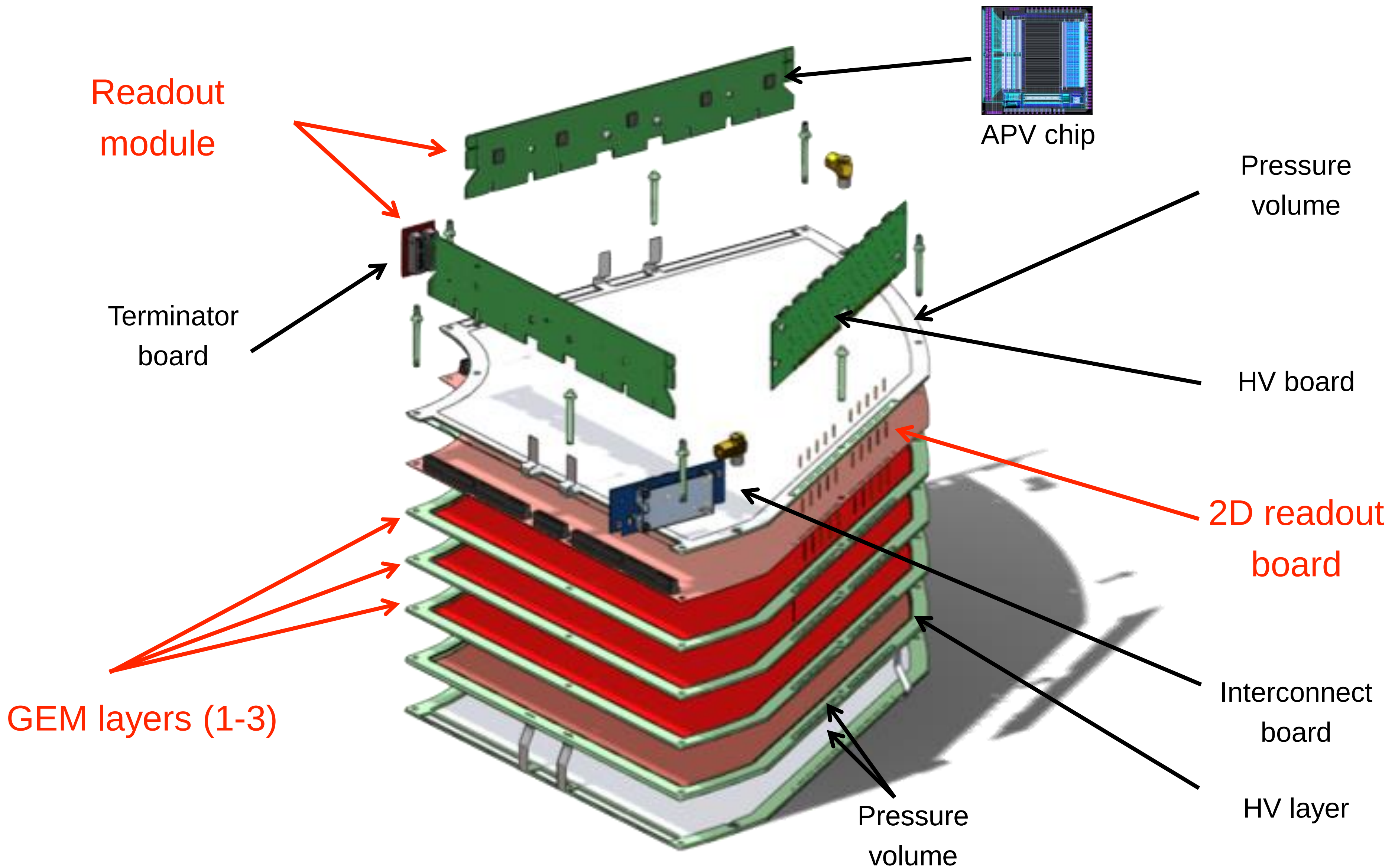


NIM A 617 (2010) 196-198

NIM A 802 (2015) 10-15

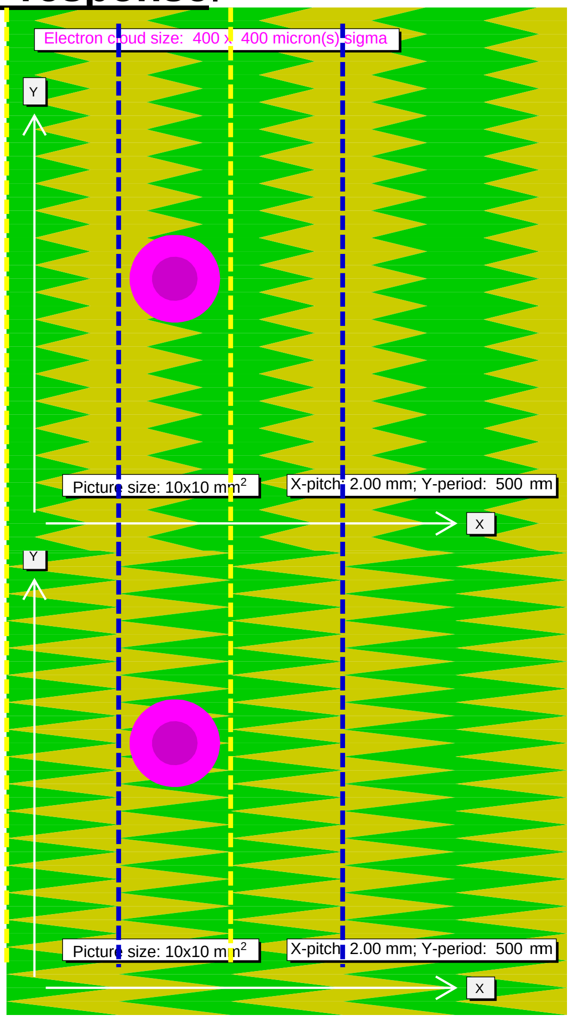
Example: Inner hole diameter distributions

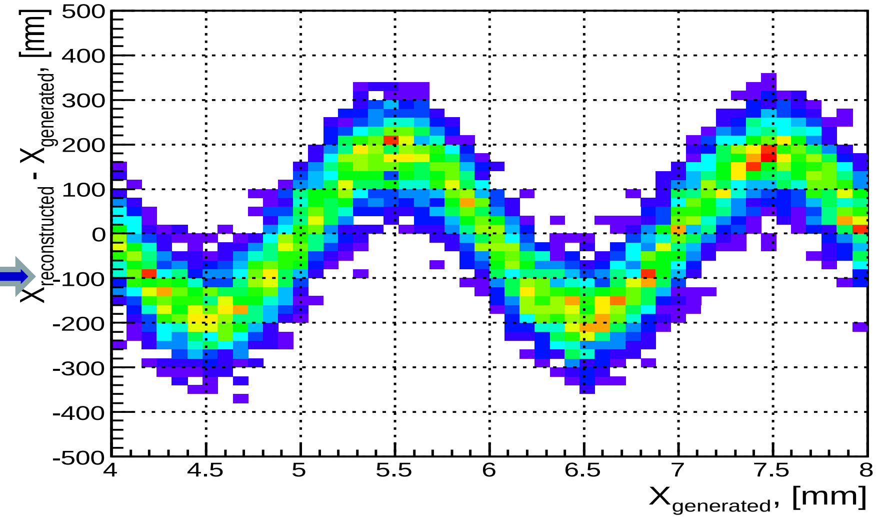
STAR FGT Quarter Section

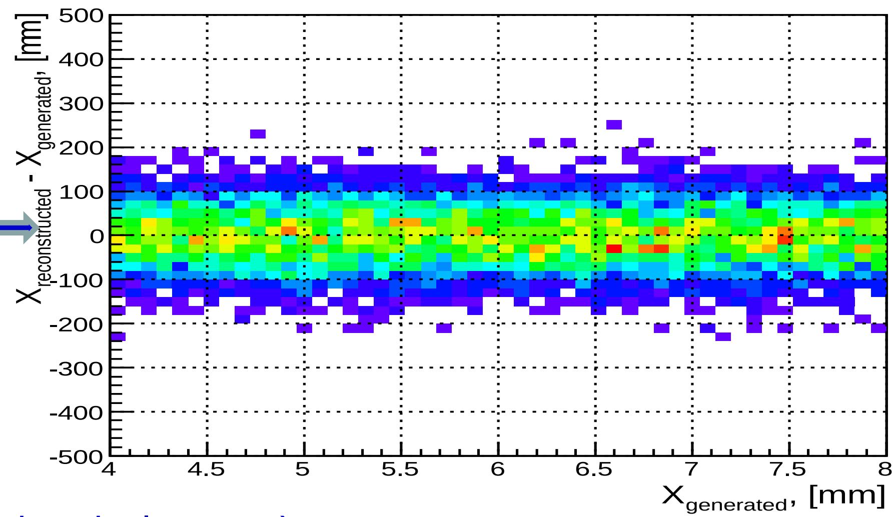


Readout design at FIT group zigzag strips

-> Type A has been tested in our previous prototype (arXiv:1508.07046), type B will be chosen for the next prototype. The reason is: **type B design gives better charge sharing and shows less non-linear response**.

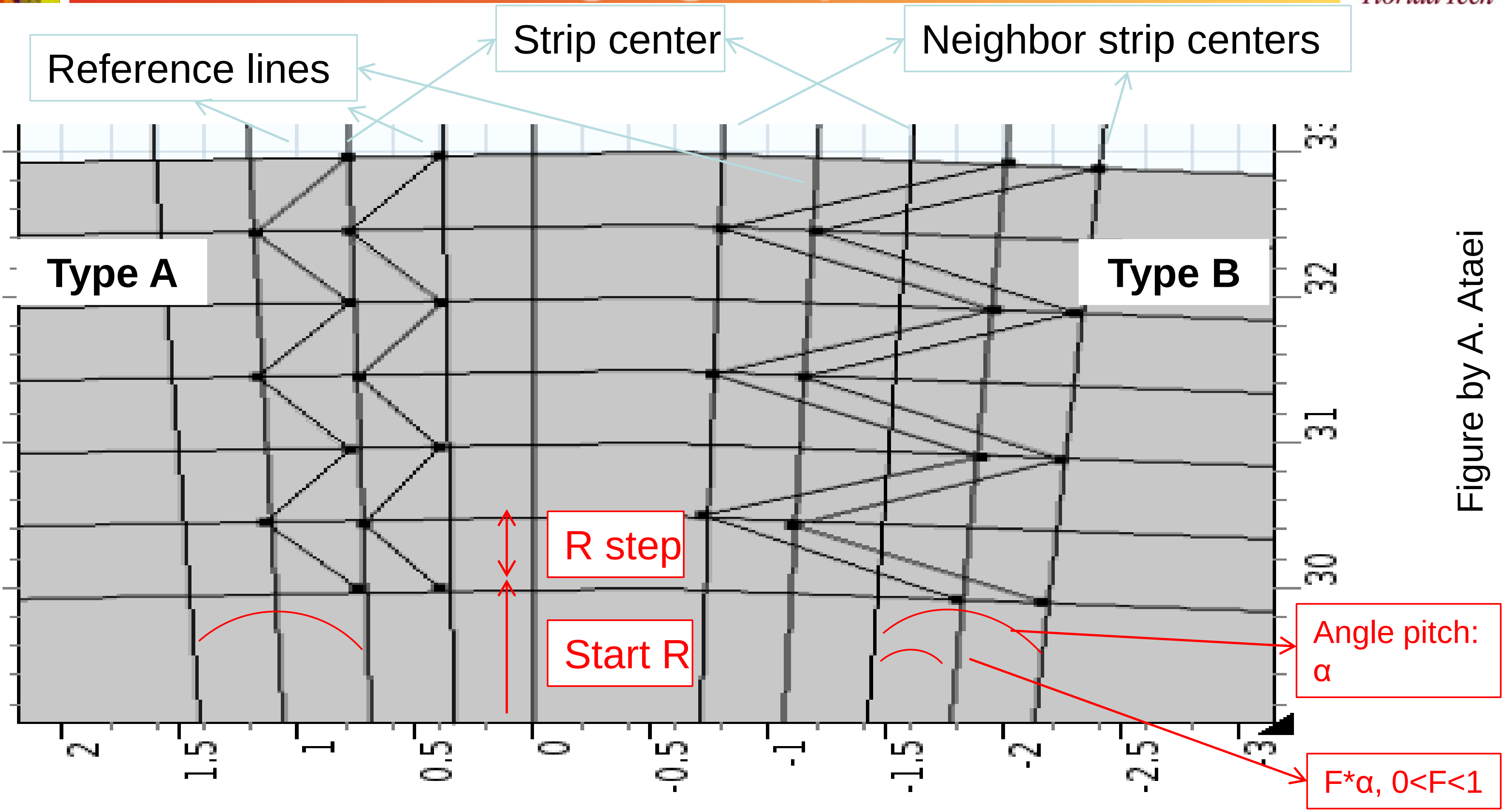






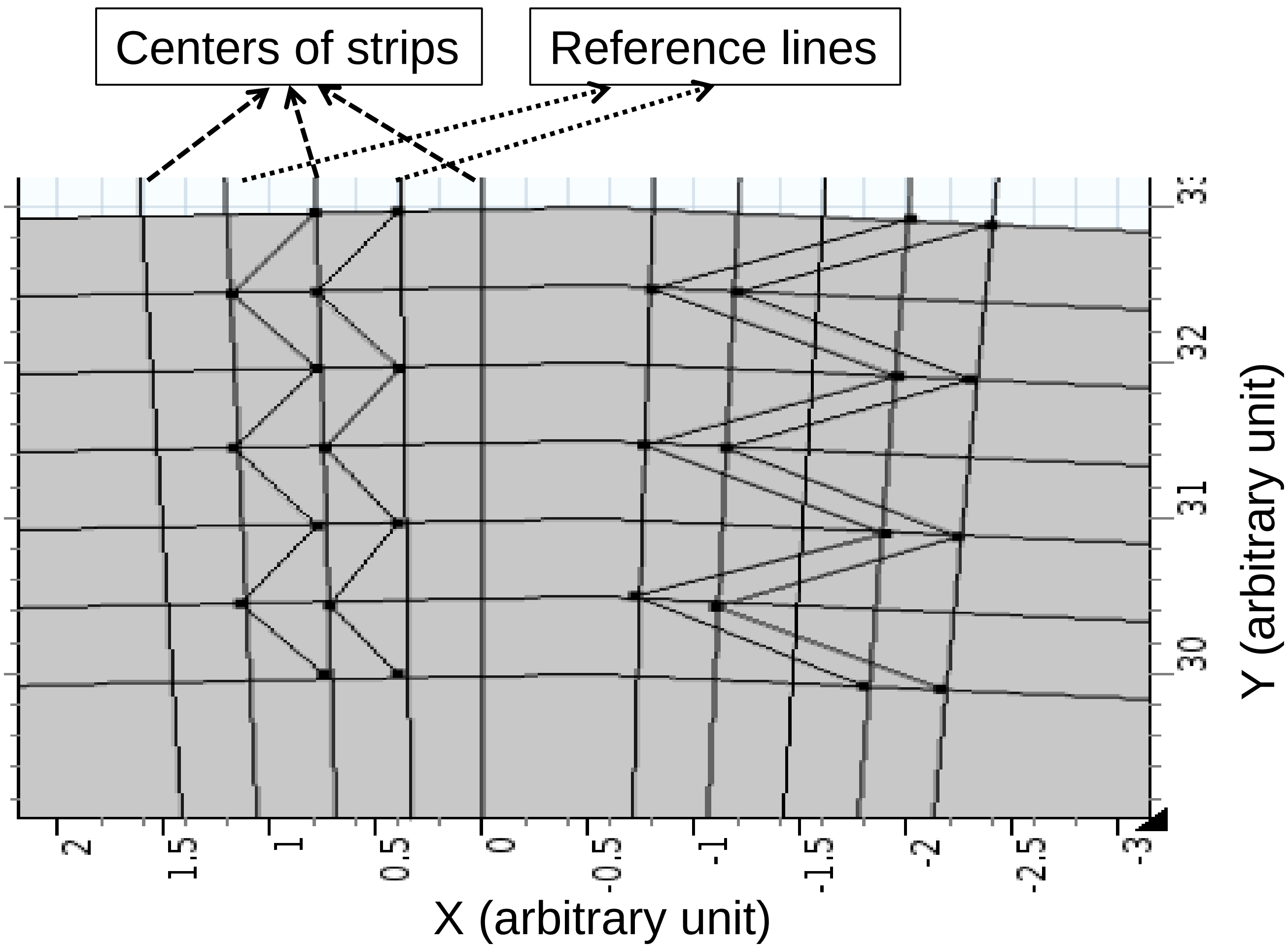
Simple model simulation results (courtesy of Alexander Kiselev, BNL)

Readout design at FIT group zigzag strips

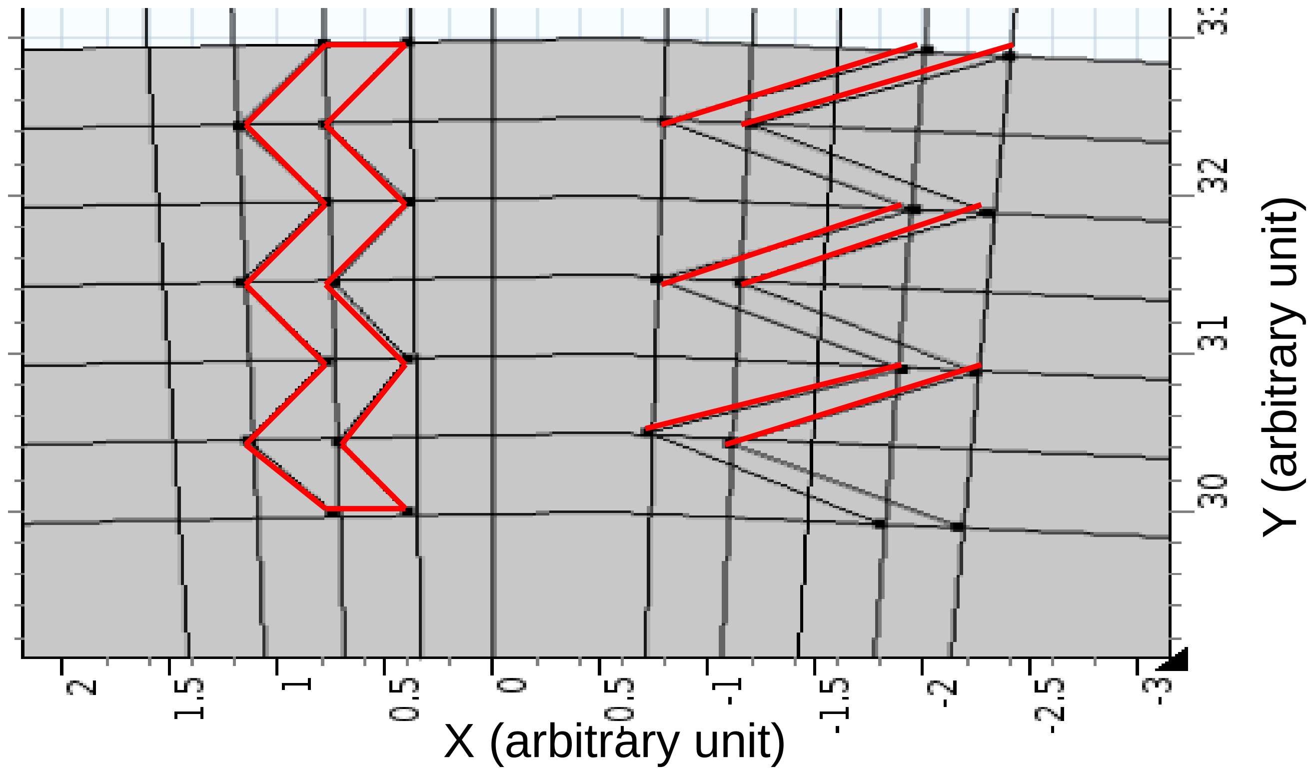


-> **Four parameters** to construct a zigzag strip: α, F, startR, stepR.

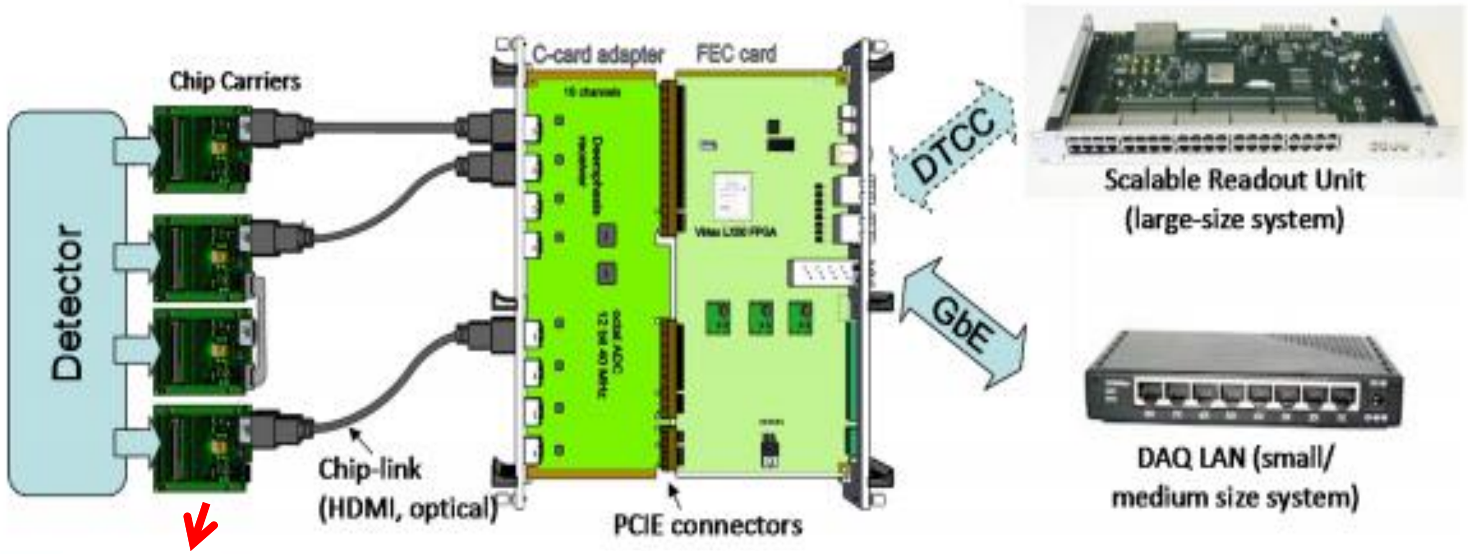
-> Two types of zigzag structure can be made: (1) type A, a zigzag strip not exceeding the <u>two reference lines</u>; (2) type B, a zigzag strip covers <u>centers of the two neighbor strips</u>.

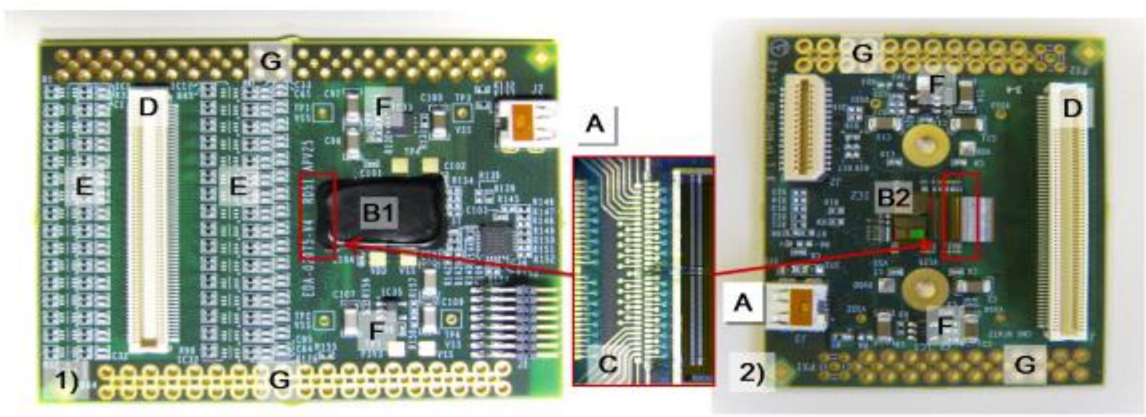


Centers of strips
Reference lines
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
X (arbitrary unit)
30
31
32
Y (arbitrary unit)


X (arbitrary unit)
Y (arbitrary unit)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
30
31
32

Electronics – SRS and APVs

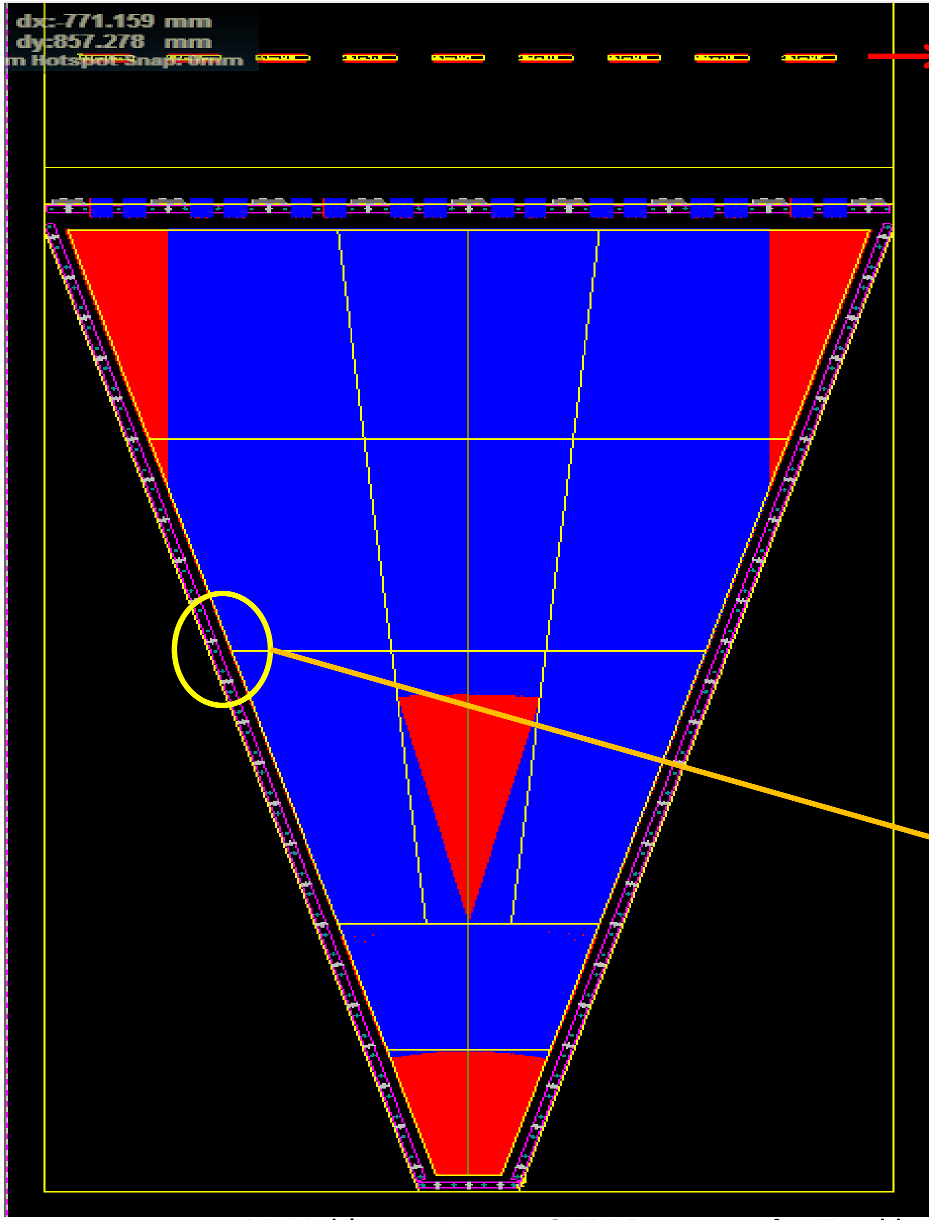




Ref.: 2013 JINST 8 C03015

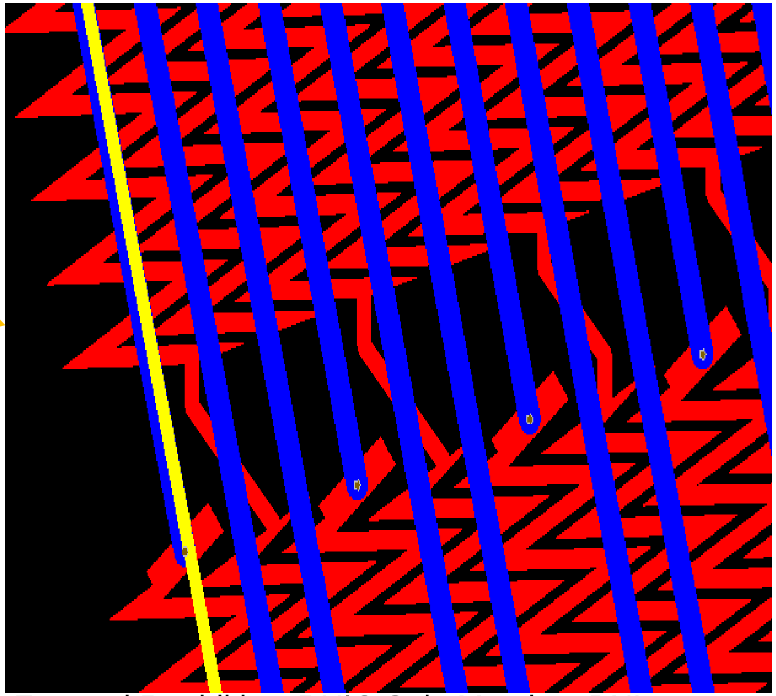
Figure 4. Front-end hybrids: 1) APV25, 2) VFAT2; A — Micro-HDMI connectors (Type-D); B1 — APV25 ASIC with top-globbing protection; B2 — VFAT2 ASIC wire-bonded; C — detail of the microvias used for the high-density wire-bond region; D — RD51 detector connectors (Panasonic); E — spark protection circuitry; F — power regulators; G — via array for the low-ohmic ground connectors.

Signal routing from readout strips to connectors



Connectors for APV chips

- **Signal lines are blue (top side)**
- **Zigzag strips are red (bottom side)**
- **Connection made with vias**

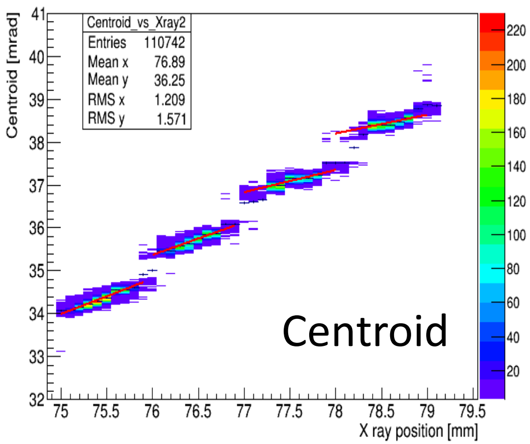


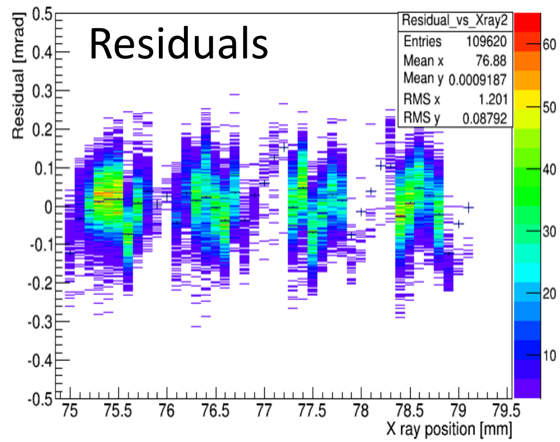
Optimization of the zigzag strip readout design – X ray scan results

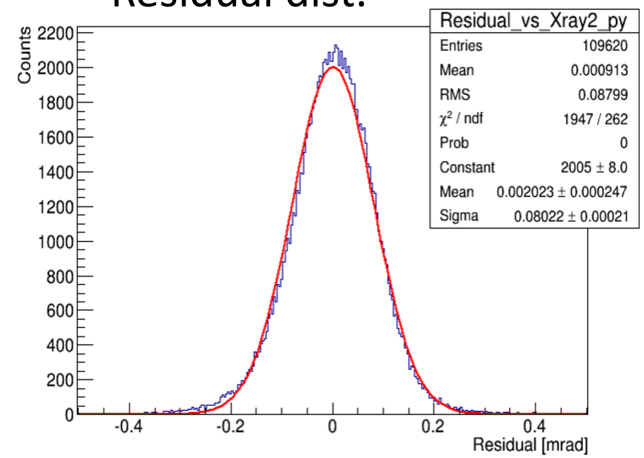
Resolution studies with CERN board for strips with angle pitch 1.37 mrad, radius ≈ 784 mm

Cluster strip multiplicity = 2

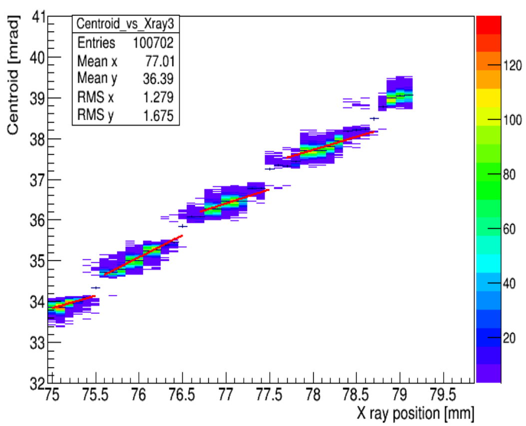
Residual dist.

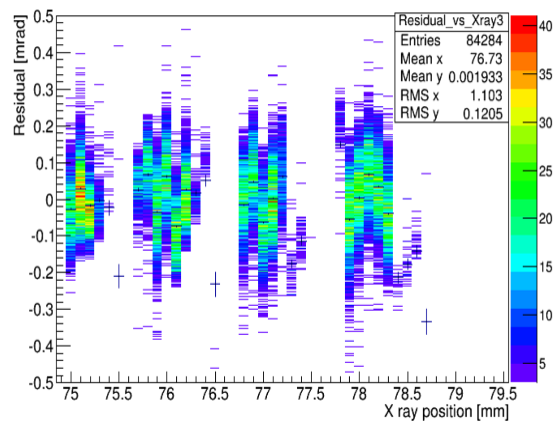


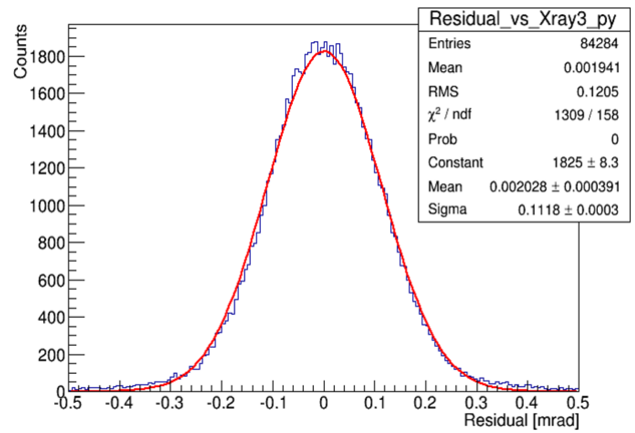




Cluster Strip multiplicity = 3







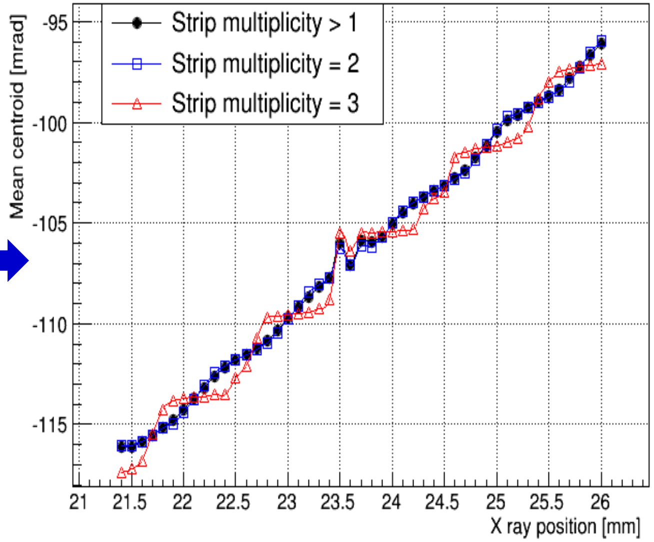
Optimization of the zigzag strip readout design – Results of X-ray scans at BNL

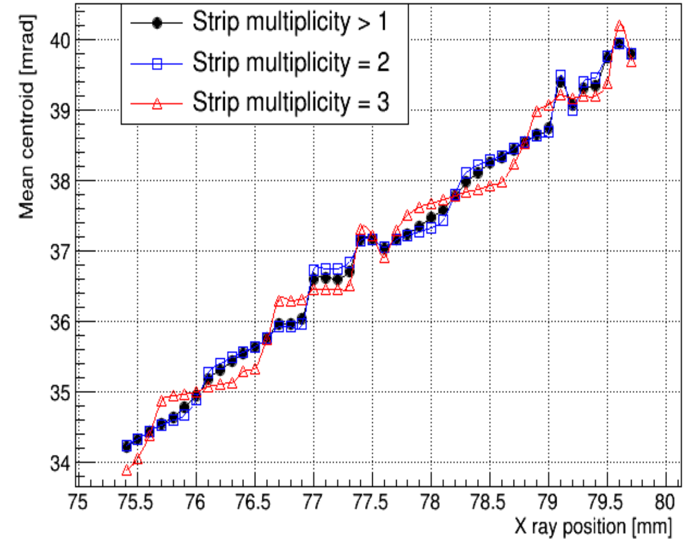
Mean centroid vs. X-ray position

Strip angle pitch **4.14 mrad**, radius in EIC ≈ **229 mm**

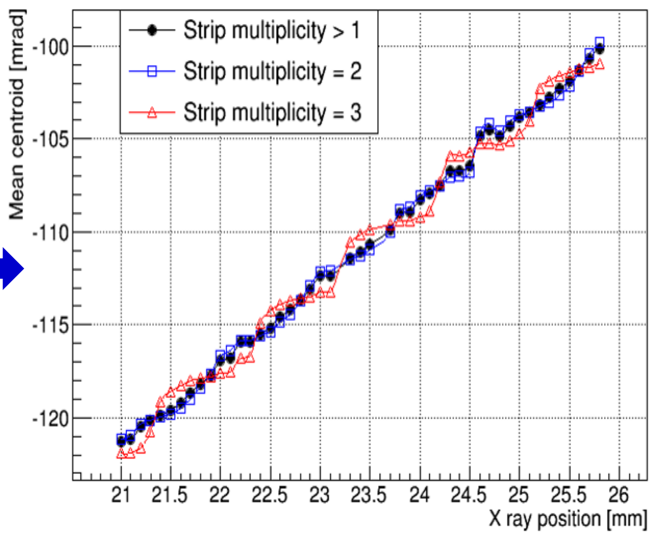
Strip angle pitch **1.37 mrad**, radius in EIC ≈ **784 mm**

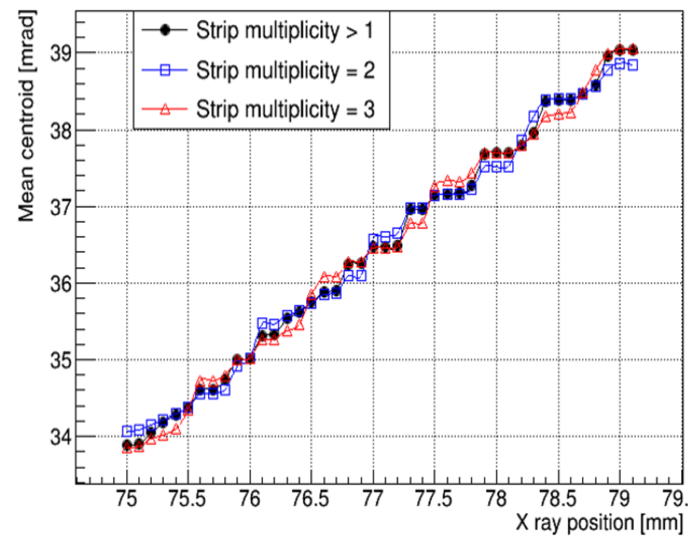
Best board from PCB comp.





CERN kapton foil board



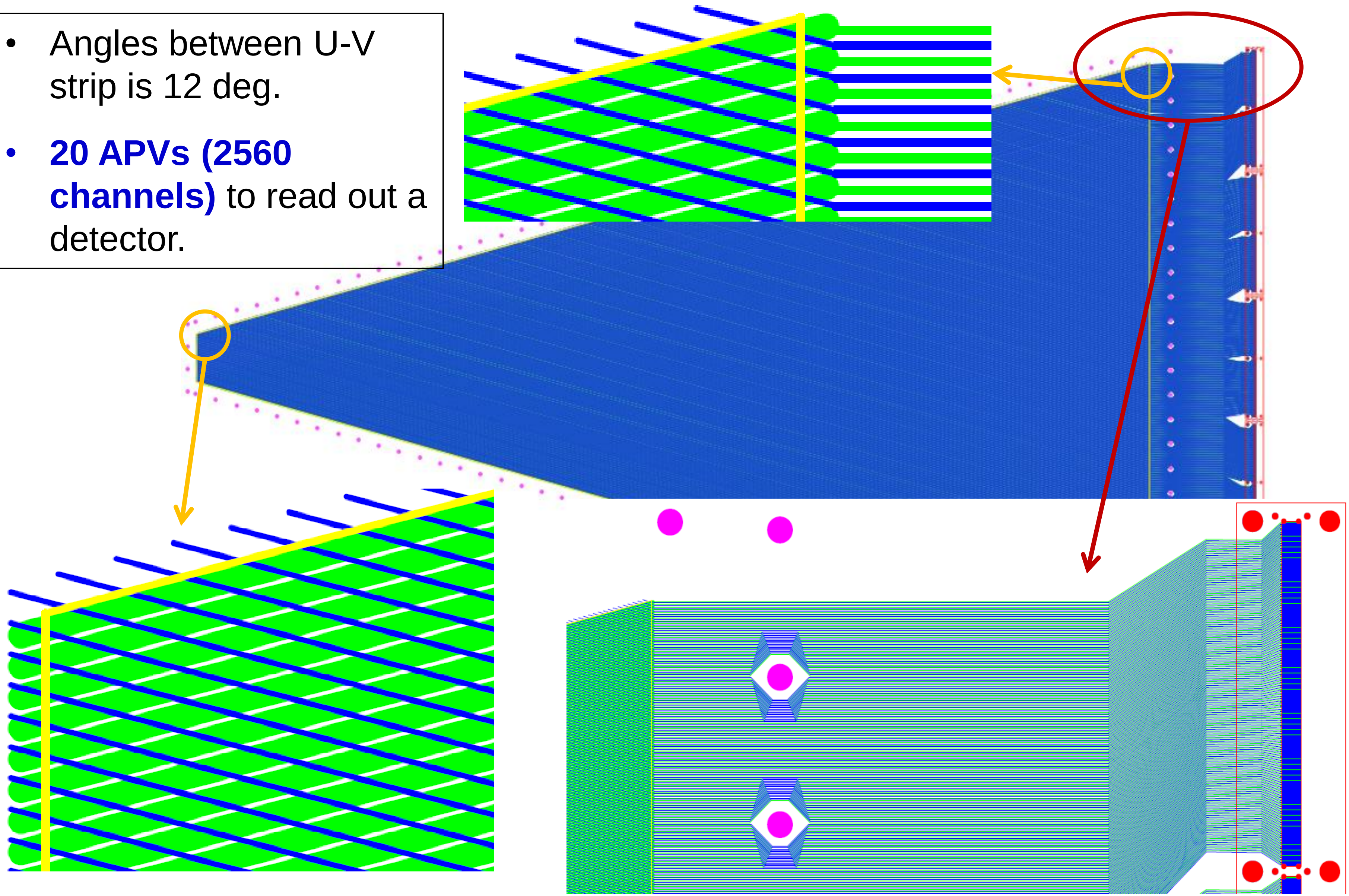


-> The response is much more linear than with the original zigzag design!

-> There are a few flat regions due to backlash of the motor when data taking was interrupted.

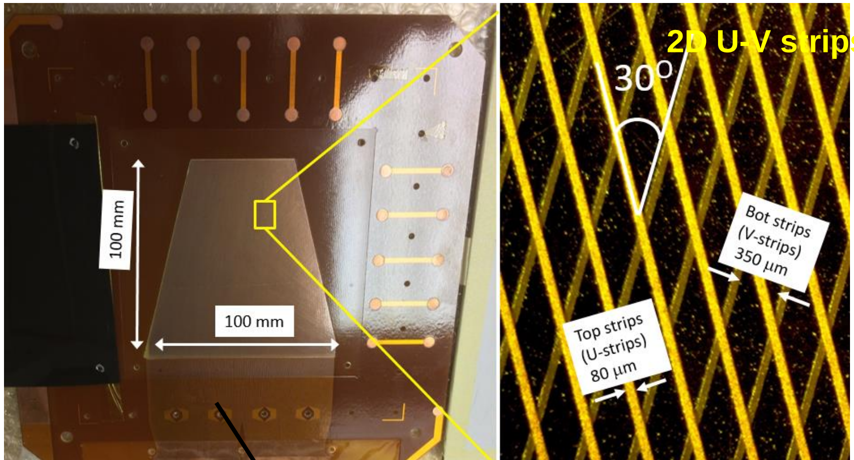
2D stereo angel strips (U-V strips)

- Angles between U-V strip is 12 deg.
- **20 APVs (2560 channels)** to read out a detector.



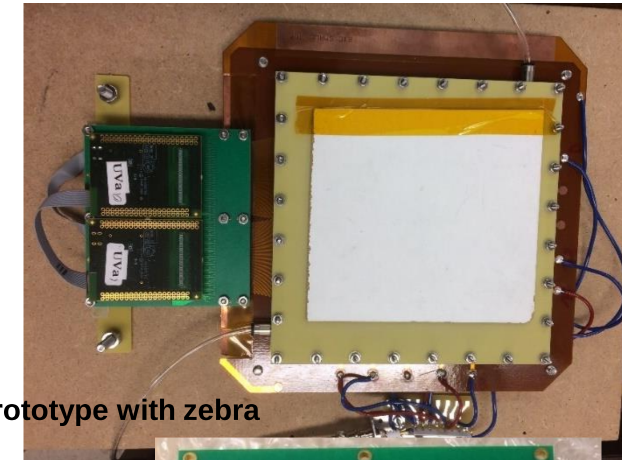
K. Gnanvo, U.Va

2D (U-V strips) readout with zebra connection concept

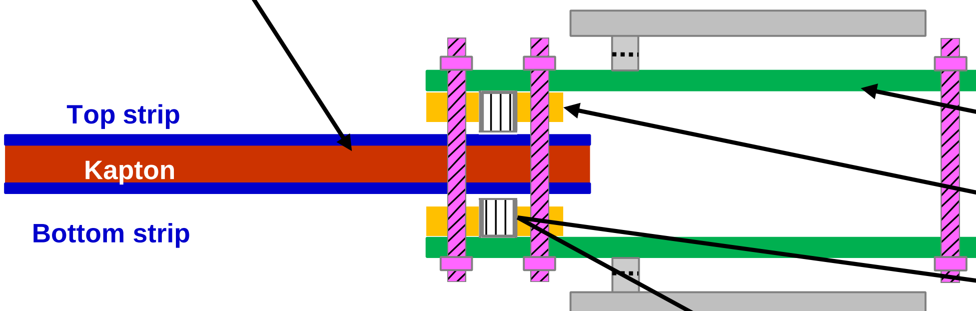


Test on a small 10x10 triple GEM prototype

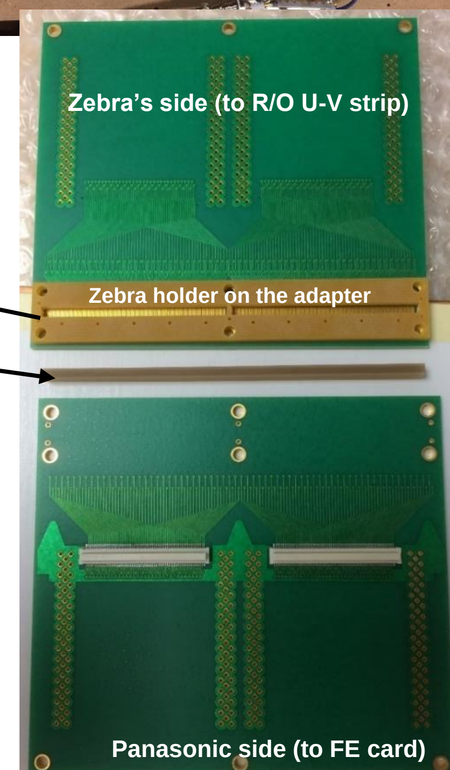
Contact of U and V strips on either side of the R/O foil

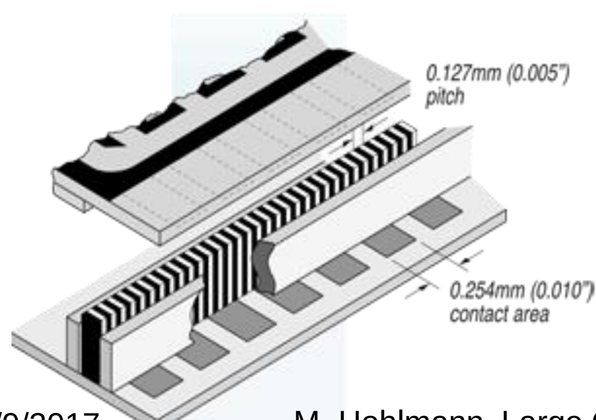


Small GEM prototype with zebra

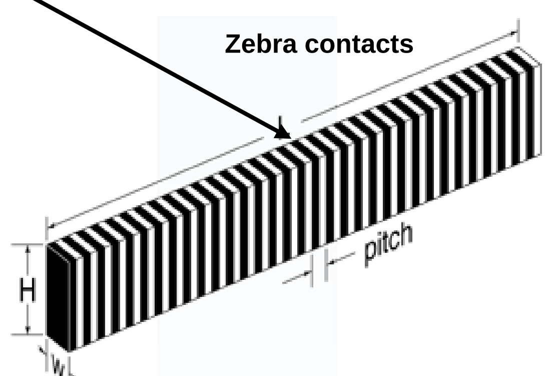


Zebra to Panasonic adapter PCB

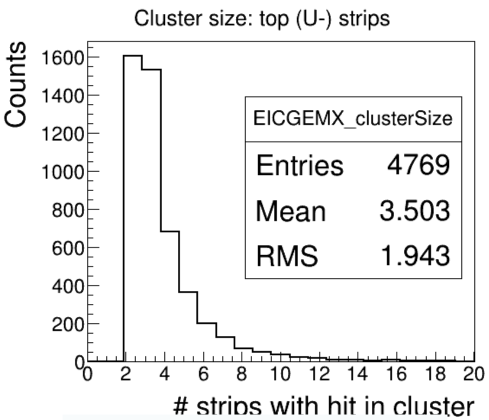




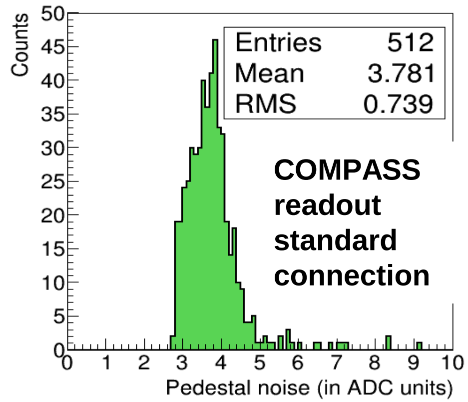
Zebra contacts

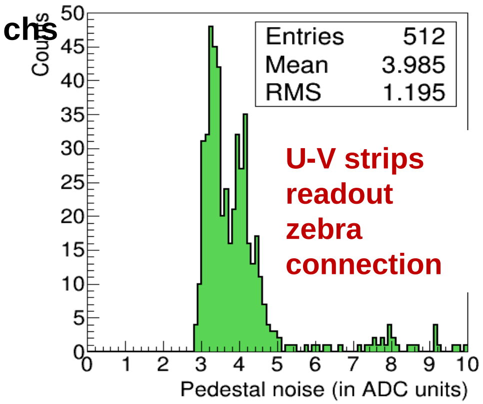


Preliminary results on small 2D (U-V strips) triple GEM prototype with Zebra connection



Distribution of pedestal rms (noises) over 512 APV25

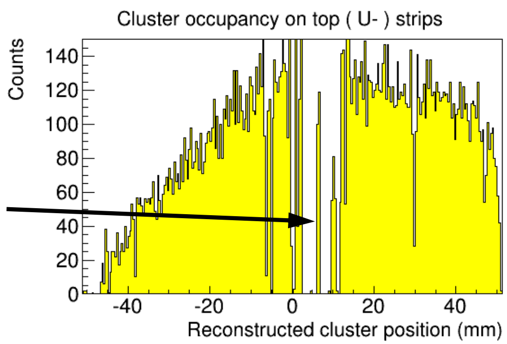


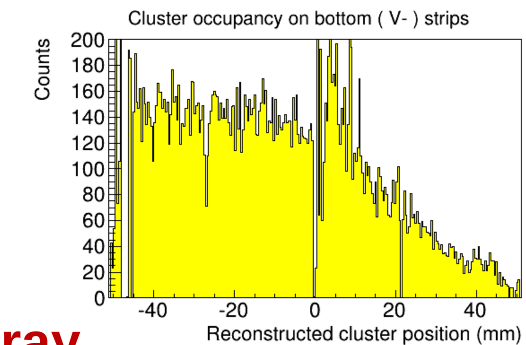


- Pedestal noise level comparable to standard COMPASS 2D readout
- No effect of the zebra connection on noise level

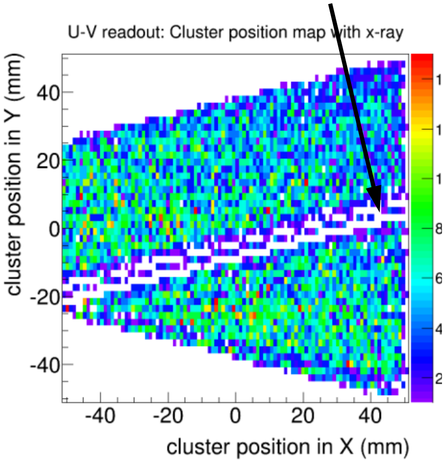
Cluster size > 3.5 ⇨ improvement in spatial resolution

bad zebra contact

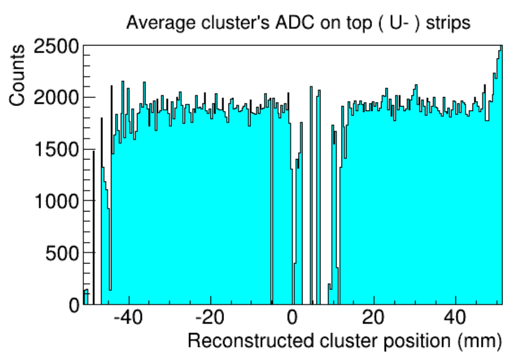


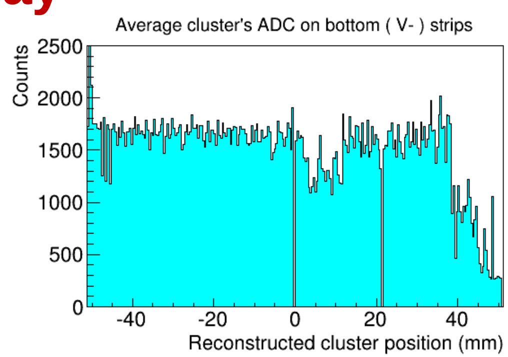


Occupancy for U and V strips: Linear dependence with strip length is shown



X-ray





Uniformity of the gain uniformity: (accumulated ADC / numbers of hits)